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CHICAGO AIR POLLUTION SYSTEM MODEL

ARGONNE NATIONAL LABORATORY

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CHICAGO DEPARTMENT OF AIR POLLUTION CONTROL

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DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE
NATIONAL CENTER FOR AIR POLLUTION CONTROL

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City of Chicago

Air Pollution System Model

ARGONNE NATIONAL LABORATORY

CHICAGO DEPARTMENT OF AIR POLLUTION CONTROL

DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE
National Center for Air Pollution Control

First Quarterly Progress Report

February 1968

by

E. J. Croke, J. E. Carson,
F. L. Clark, A. S. Kennedy,
and J. J. Roberts

ENVIRONMENTAL SCIENCES

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FOREWORD

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Program direction, system analysis and computer programming are provided by the Argonne National Laboratory. Meteorology studies and computer model development are performed by Argonne and the National Center for Air Pollution Control, Cincinnati, Ohio. The Chicago Department of Air Pollution Control supplies emission and air quality data for the atmospheric dispersion studies.

The first quarterly progress report which follows is necessarily somewhat broad in scope, since it treats not only the actual progress achieved during the first three months of the program, but also provides an overall perspective of the dispersion modeling problem as Argonne views it and describes the general plan for this first phase of the air pollution program. It is expected that subsequent reports will be somewhat less comprehensive, since they will consist almost solely of a summary of actual program progress.

PREFACE

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CHICAGO AIR POLLUTION DISPERSION MODEL

1.0 Introduction

E. Croke

CHICAGO AIR POLLUTION DISPERSION MODEL

1.0 Introduction

1.1 Program Objectives

The Chicago Department of Air Pollution Control, the Department of Health, Education, and Welfare and the Argonne National Laboratory are engaged in a joint effort to develop a computer program which will predict the dispersion of sulfur dioxide produced by coal and oil-fired plants in the City of Chicago.

If such a computer program can be developed, three advantages will result:

1) It will be possible to forecast the severity of air pollution incidents with some degree of precision and to establish an effective pollution warning system.
2) It will be possible to develop economical and optimum air pollution abatement strategies to minimize the severity of pollution incidents. Such strategies would include switching major industrial or power plants which are equipped with dual fuel capability from coal to natural gas during severe pollution incidents and shifting of the electrical power load from upwind utility installations within the city to downwind or out-of-city plants. Other possibilities include the use of low sulfur content coal or oil in nonconvertible plants, etc. To implement such a strategy at minimum cost and with minimum disruption of normal operations is one of the primary purposes of developing a computerized pollution forecasting method.
3) Long-range city and county planning will be able to take account of the air pollution problem in the development of zoning ordinances and the layout of residential, industrial, and commercial areas. Pollution control legislation can be based on a realistic evaluation of the effects of various sources and control devices on the quality of Chicago's air.

In order to develop an effective computerized system for the prediction of sulfur dioxide dispersion, three kinds of data are required:

1) Records of the meteorological situation in Chicago. These are needed because of the dominant influence exerted by meteorological factors on the ability of the atmosphere to dilute and disperse pollutants.
2) Historical records of the air quality in the city - specifically the time variant and spatial distribution of sulfur dioxide concentrations over the Chicago area.
3) Records of the amount of sulfur dioxide released in the city by residential, commercial, industrial, and power plants.

The meteorological and air quality data required for the computer program are available from Weather Bureau records and from the network of meteorology and sulfur dioxide measurement stations which has been operated by the Chicago Department of Air Pollution Control since January 1966. Continuous records of the meteorological situation and the sulfur dioxide concentration (parts per million of SO_2) measured at stations distributed throughout the city) are available for the period January 1966 to the present.

The remaining essential component of information that must be obtained in order to construct the computer program is emission data for the major sources in the city. Some of this emission data is relatively easy to obtain. For example, the utility plants return detailed hourly power generation records which can be directly correlated with sulfur dioxide emissions. A similar situation prevails for the large University of Chicago heating plant. In other cases, however, plants that contribute significantly to the sulfur dioxide background in the city may have no more detailed records than annual coal consumption figures. For large space-heating plants, this kind of information is largely adequate because it is possible to correlate the output of a heating plant fairly well with meteorological records, but for large processing plants only a minor part of the fuel consumed may be used for heating purposes. For such installations, it is necessary to devise other methods of reducing annual or monthly fuel consumption records to hourly data. Whether this is accomplished by correlating with production records, operating history, electrical power usage or other historical information depends largely on the type of plant being considered and the kind of records that it keeps.

When the necessary air quality, meteorological and emission data inventory has been acquired, these parameters must be related by a set of physical or statistical laws which describe the behavior of the system. The aggregate of these three types of data and an adequate statement of the laws which govern the system constitutes a "model" of the air pollution dispersion process.

1.2 Discussion and Program Summary

The development of air pollution dispersion models has been undertaken for a number of major cities or regional areas, including St. Louis, New York City and the state of Connecticut. All of these models are similar in the sense that each represents an attempt to devise a deterministic, physical simulation of the dispersion processes in the atmosphere. None of these has yet been developed to the point of yielding consistently reliable air quality estimates of sufficient accuracy to allow an air pollution control engineer to make real-time decisions regarding measures that should be taken to prevent or abate an air pollution incident. The limited success achieved to date by various multi-source dispersion models is indicative of the fact that our understanding of the complex physical processes that influence the micro-meteorology of an urban concentration or other limited regional area is, as yet, far from complete, and that the extensive inventory of meteorological data necessary to define and model these processes has not yet been accumulated in sufficient quantity or quality. It does not necessarily follow that these deficiencies will always exist, nor does it follow that one or more of the sophisticated physical models now in development cannot be refined to the point of yielding adequate pollution forecasts - even within the context of the present state-of-the-art, but it did not appear that Argonne could contribute in any significant way to the state-of-the-art by undertaking the construction of yet another model of the same general kind that are already being developed.

In the effort to develop a dispersion model for Chicago, Argonne was in a position to exploit a significant advantage that was not available in other cities or areas. This was the inventory of near real-time air quality data accumulated since January of 1966 by the Chicago Department of Air Pollution Control (DAPC). Integrated average wind vector and SO_2 concentrations recorded at fifteen minute intervals at eight stations strategically distributed within the Chicago metropolitan area yielded an unequalled volume of historical air quality and meteorological data.

The availability of this large data inventory and the Argonne commitment to develop a working pilot dispersion model within the context of a 12 month study program suggested the possibility of constructing an empirical, statistical model rather than a physical, deterministic model of the kind hitherto attempted. By statistically "force-fitting" air quality data into a matrix which included standard meteorological parameters and SO_2 emission data, it appeared that a semi-empirical, computerized pollution forecasting technique might be developed which would circumvent many of the difficulties inherent in the attempt to simulate complex atmospheric diffusion processes.

To this end, an effort was mounted to obtain hourly SO_2 emission data for Chicago over the same time period within which the DAPC air quality data was accumulated. Concurrently, a study of the micro-meteorology of Chicago, in the context of air pollution dispersion, was initiated. Parallel studies of atmospheric dispersion theory and of existing air pollution dispersion models were undertaken, and the computer programming effort necessary to process the data associated with the emission inventory and air quality records was begun. In parallel with the mainstream effort to construct a statistical model, a cooperative program to refine and improve the physical dispersion model currently being developed for St. Louis under the auspices of the Public Health Service was undertaken in order to provide an alternative resource in the event that the statistical approach should prove unfeasible.

Functionally, the Argonne statistical modeling program may be divided into four major areas of effort. These are:

1. Diffusion Analysis
2. Meteorological Studies
3. Emission Inventory
4. Computer Programming

Certain tasks and sources of information are associated with each of these functional areas. These are reflected in figure 1.1 which summarizes the Argonne dispersion modeling effort, and are discussed in detail in subsequent sections of this report.

Ancillary to the development of a dispersion model is the initiation, during the first phase of the program, of preliminary studies in the area of the economics of air pollution abatement. These studies represent in a sense, an introduction to the second phase of the Argonne air pollution program, in which the development of abatement strategies and the evaluation of the economic implication of these strategies constitute the mainstream effort. This report therefore contains a brief discussion of a proposed optimal abatement gaming strategy which could be evaluated during the current phase of the program and which would serve as a precursor of the more comprehensive studies to be conducted in the second phase.

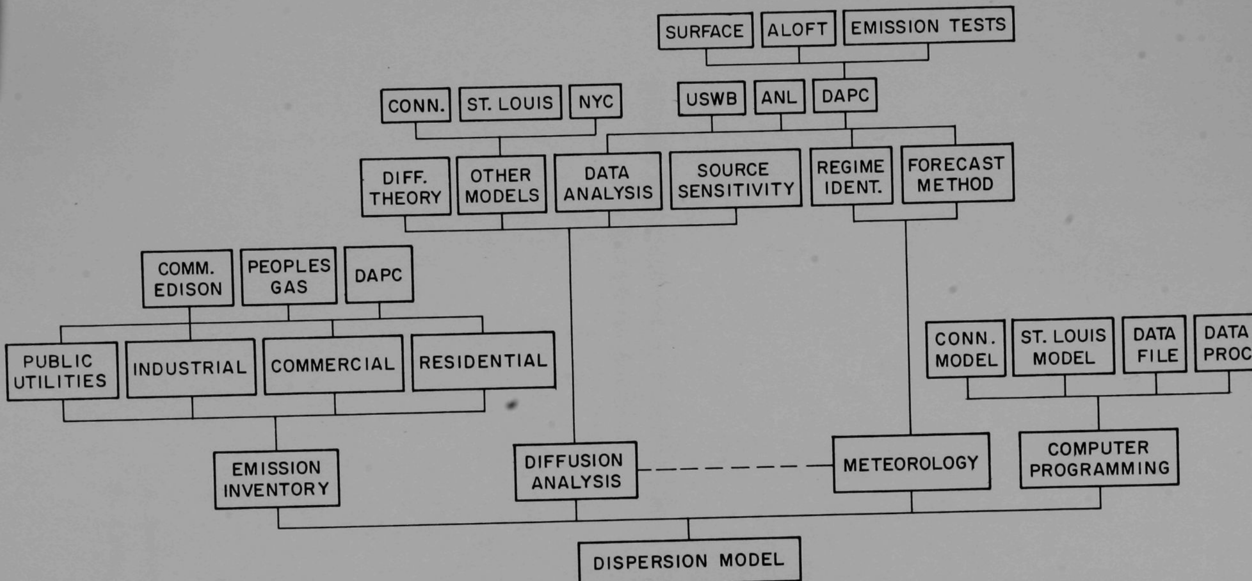

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Fig. 1.1 Program Structure

CHICAGO AIR POLLUTION DISPERSION MODEL

2.0 Diffusion Analysis

J. Roberts

E. Croke

2.0 Diffusion Analysis

2.1 General Discussion

Diffusion models have been developed for the purpose of describing the dispersion of pollutants (notably SO_2) over urban areas[1,2,3]. Without reviewing the details of these models, one can generalize that almost all attempt to follow each plume or puff of pollutant from its source with SO_2 concentrations described by gaussian kernels about the centerline of each predicted trajectory. The key to success is then clearly related to the accuracy of the emission inventory and the validity of the transport assumptions, in particular the σ_x, σ_y and σ_z values used in the gaussian kernel. These latter parameters are usually obtained from experiments conducted over homogeneous terrain quite unlike the cityscape although occasionally subjective modifications[4] are made for the urban environment and, in at least one case, two free parameters are available to fit the model to observed data[3].

Considering the requirement that Argonne produce, within one year, a real time computer program to estimate accurately the SO_2 concentration in Chicago, it seems advisable to investigate the possibility of adapting one of the more established urban models, in particular St. Louis or New York since these are cities of complexity comparable to Chicago. The emission inventory that is being compiled by ANL and the Chicago Air Pollution Control Department has sufficient detail for these models. The Chicago meteorological data is comparable to the St. Louis study but lacks the sophistication necessary for the New York formulation for which helicopter soundings provide information on inversion layers and as many as 40 reliable wind measurements supply the details of the wind field.

The success of these two models for pollution mapping over a large urban region has yet to be demonstrated. If the St. Louis model is tested successfully, it could be adapted quite readily to the Chicago area. (See section 2.3)

As regards the New York model, even if it were made to predict SO_2 accurately for a sufficiently large region, Argonne would probably be frustrated in an attempt to apply it in 1968 because the requisite meteorological input is lacking - especially since a real time prediction capability is desired. Rather, the New York prototype, if successful, might delineate a program of meteorological instrumentation throughout Chicago and Cook County which, after perhaps a year or two, could provide real time input to an on-line version of the New York model. To this effect, a helicopter sounding program and the installation of instruments to measure the vertical temperature profile have been scheduled for 1968 by the Chicago DAPC.

The predictive accuracy of any model must be ascertained by comparison with actual SO_2 observations. Whereas most models are designed to handle all possible meteorological conditions by such generalizations as the formulation of objective stability criteria, they have not been tested adequately, since SO_2 measurements have not been made for a statistically significant sampling of all possible meteorological patterns. This is particularly important where the comparison between theory and experiment has been based on twenty-four hour averages during which the pollution dispersion may be influenced by several changes in stability criteria. Chicago is unique in this matter since SO_2 has been monitored every fifteen minutes at each of the eight TAM stations since January 1966. Therefore, instead of reserving the SO_2 measurements solely for the evaluation of the model, it seems advantageous to incorporate these many observations in the actual construction of the Chicago model. Basically our intention is to correlate known emissions or emission patterns with observed SO_2 values at each of the eight receptors. As will be discussed in the following section, this approach should assure excellent predictive capability, the main problem being one of filtering the SO_2 and emission data to see the SO_2 signals from each significant source relative to the background from all other sources and the inherent noise so that the contribution of each source to any receptor can be evaluated. This involves the estimation of coupling coefficients between each significant source and each receptor for all plausible meteorological conditions (conceptually similar to the gaussian kernels of earlier models evaluated at a particular point $\{t,y,z,u\}$). Eventually, these coupling coefficients can be fit to some algebraic generalization such as the gaussian kernel which might then be incorporated in a model similar to that for St. Louis. However, in contrast to earlier models, this is the end product of a statistical correlation which should automatically incorporate the inhomogeneities of the Chicago landscape.

2.2 Statistical Model for SO_2 Prediction

This section outlines what is anticipated to be the initial approach to the formation of a dispersion model based on statistical correlation between known emissions or emission patterns and observed SO_2 values. Since the technique has yet to be tested, it seems reasonable to expect that future successes and failures will dictate modifications in the model building process. By following this adaptive philosophy and by testing our theories on asmall scale for a single receptor and its associated sources, we hope to evaluate our statistical approach within the next few months. The Hyde Park telemetered air monitoring (TAM) station was chosen for the purpose of this pilot study.

2.2.1 Pollution Regimes

In almost all plume theories, a set of criteria including such observables as time of day, gustiness, and insolation is employed to determine the existence of a particular stability classification. This then determines parameters in equations such as the one used by Turner in the Nashville study[1]

$$\sigma_y(t) = a\ t^b.$$

In other words, it is assumed that each proposed set of meteorological parameters determines a regime within which certain atmospheric dispersion properties or relationships remain constant, or approximately so.

In a like manner, stability classifications, or pollution regimes as we have chosen to call them, will be established for the Chicago area. The criteria employed will emphasize meteorological conditions peculiar to Chicago, such as the lake breeze, as well as more traditional parameters such as cloud cover. Some preliminary observations in the study of Chicago air pollution regimes are presented in the meteorology section of this report. In the following discussion it is assumed that the statistical estimation of coefficients will be performed separately for data in each of the chosen pollution regimes. This then points out a problem; that while these regimes must be restrictive enough to achieve their purpose, they must be sufficiently general to include a significant number of data points.

2.2.2 "Met. Set" and Significant Point Sources

A relationship is to be determined via a linear regression analysis which correlates SO_2 observations at each of the eight TAM receptors with known emission patterns such as one due to residential heating and known emissions from large point sources. Numerical coefficients in the overall pollution model will be evaluated in a stepwise fashion by considering one TAM station at a time. The Hyde Park station will be studied first. Pollution regimes, wind sectors, and wind speed bands will be specified - each combination of these three items to be considered separately as a particular "Met. Set". For example, the concurrence of the three criteria: winds of gustiness class B_1 from the Sector 270°-300° with speeds between 6 and 8 mph might specify the existence of a single met. set. Thus the SO_2 data for each TAM station will be partitioned and analyzed according to the proposed met. sets.

The point sources included in each regression analysis will depend upon the chosen met. set, in particular upon the wind sector, since one would certainly expect close-in, upwind sources to dominate the SO_2 observations. Thus for each wind sector and wind direction a set of "significant sources" will be determined for inclusion in the regression analysis and the efforts of the emission inventory will be concentrated on obtaining details of the selected plants.

The preliminary determination of whether or not a given source is a significant source for a particular TAM station and met. set will be based on a direct application of the plume equation and coefficients given by Turner for the Nashville model[1]. The selection process will emphasize the relative contributions of different upwind sources to the receptor.

2.2.3 Mathematical Statement

The mathematical statement relating SO_2 concentrations, X_n, and the significant emissions for a chosen TAM station and met. set has the form:

$$X_n = B + H_1 P_{1n} + H_2 P_{2n} + \sum_{i=1}^{I} K_i Q_{in}$$

$$n = 1,\ldots,N$$

$$N >> I + 3$$

The subscript n refers to a particular hourly average of that known quantity. Although this subscript runs from 1 to N, the corresponding hours need not be consecutive. Whether or not a single isolated hourly value will be considered as a valid data point is unclear at this point in the study.

The constants B, H_1, H_2, and K_i, i=1, I are coefficients to be determined by linear regression. B represents a constant background - for example, a "hold fire" is maintained at all times throughout the year in almost all automatic stoker fired coal boilers.

The function P_{1n} describes the hourly emission pattern of residences with automatic stoker fired boilers. This function, which will be discussed in more detail in the next quarterly report, takes into account the outside hourly average temperature (probably by its deviation from a reference such as 65°F), the time of the day or "janitor function" (for example, regardless of the temperature, only the hold fire is maintained between 12 midnight and 4 AM), and possibily other parameters such as wind speed and sunlight if meaningful relationships can be found between fuel consumption and these quantities of lesser significance.

Emission pattern P_{2n}, similar in concept to P_{1n}, describes the fuel consumption of large buildings and complexes such as the Chicago Housing Authority projects which operate high pressure steam heating systems. Since these heating units run day and night, they must be represented by a different fuel use pattern than the typical six-flat pattern, P_{1n}. The collection of emission data to develop P_{2n} is discussed in the Emission Inventory Section of this report. The function P_{2n} will probably be evaluated via a separate regression analysis using Chicago Housing Authority and University of Chicago data.

The terms $K_i\ Q_{in}$, $i=1,\ldots,I$, represent the contributions from significant point sources, where Q_{in} is the hourly average SO_2 emission from source i during a particular hour preceding the actual observation X_n. Symbolically, one could write $K_i\ Q_{i,n-\tau_i}$ where τ_i represents the transport delay between source i and the detector (for the chosen wind speed). Although the data is handled in this manner, the simpler subscript n is used in the mathematical notation to signify the value of source Q_i associated with the measurement X_n at time n. K_i is the coupling coefficient or conversion factor between the emission Q_i and the receptor for a given met. set. As mentioned earlier, it corresponds to the evaluation of a plume dispersion kernel. For example, it represents a particular numerical value of X/Q in Turner's model of Nashville, which is based on the equation:

$$\frac{X}{Q} = \frac{\exp\left[-\frac{1}{2}\left(y^2/\sigma_y{}^2 + H^2/\sigma_z{}^2\right)\right.}{\pi\ u\ \sigma_y\ \sigma_z}\ .$$

However, the X/Q values for Chicago will be found empirically rather than by the use of objective stability criteria and associated predetermined functions for σ_y and σ_z. It should be evident that several K_i values could be combined to yield σ_y and σ_z functions. Thus our statistical model may in due course be merged with a model such as that for St. Louis or New York to yield a resultant prediction scheme that is both statistically and physically satisfying.

2.2.4 Accuracy of Prediction. Although it is certainly premature to extol the virtues of the statistical approach to modeling, some estimate of its prediction capability can be obtained from the single model

$$X_n = B$$

applied to a particular TAM Station for a given met. set. This has been done for the Hyde Park Station using data from three winter months, January, February, March, 1966. The unsophisticated pollution regime - hours between 0060 and 1700 on weekdays for days with greater than five hours of sunshine and degree-day values between 40 and 60 - was chosen primarily because it was easily identifiable on the Weather Bureau summaries from Midway Airport. In accord with the two wind speed and direction bands listed in Table 2.1, the TAM hourly average SO_2 readings were assembled and averaged to yield the results shown in Table 2.1

Table 2.1

Model: $X_n = B$ for Hyde Park TAM Station

	1	2
Wind Speed Band	6 - 8 MPH	9 - 11 MPH
	3	4
Wind Direction Band	260 - 290 DEG	300 - 330 DEG

Results and RMS Deviation from Observed Concentrations

$B_{13}^{*} = .48 \pm .14$ ppm (21 data points)

$B_{14} = .60 \pm .11$ ppm (11 data points)

$B_{23} = .31 \pm .15$ ppm (12 data points)

$B_{24} = .48 \pm .17$ ppm (6 days points)

*Subscript 13 implies wind speed between 6 and 8 mph and wind direction between 260° and 290°.

As one would expect, SO_2 concentration varies inversely with wind speed, i.e. $B_{13} > B_{23}$ and $B_{14} > B_{24}$. Furthermore, it seems that although the two sectors view somewhat similar residential patterns, sector 300°-330°, which contains more significant point sources, has the higher mean SO_2 concentration; i.e., $B_{14} > B_{13}$ and $B_{24} > B_{23}$. An inspection of the hourly trends in SO_2 and temperature indicates that a significant portion of the error can be removed by incorporating some form of hourly space heating correlation such as P_{1n} and P_{2n} which are strong functions of the hourly temperature. We therefore have good reason to assume that the proposed model will have excellent predictive capability which, of course, it should, since it is based on actual receptor readings. However, the success of the model also depends on another important aspect, epitomized by the following question: Having introduced a space heating correlation and thereby considerably reduced the variance in Table 2.1, can we further reduce this variance in a statistically significant manner by correlation with one or more significant point sources? Success in this matter will be especially difficult for the Hyde Park TAM Station since it is surrounded by coal burning three story residences. However, it will be necessary eventually to identify the coupling coefficients of significant point sources if we are to develop a pollution incident abatement program based on fuel shifting (coal to gas) for selected utilities and industries or load shifting for the utilities.

2.3 Physical Dispersion Model

If the pilot version of the statistical dispersion model proves successful, it is intended that it will, in due course, be merged with a physical model - or at least be modified to reflect more effectively the deterministic physical processes that influence atmospheric dispersion. The nature of the kernel of this physical model has not yet been established, but it appears likely that a scheme of the kind employed for the Connecticut[2], New York[3], or St. Louis[4] models would be appropriate. At the present time, in any case, the validity of the statistical approach remains to be demonstrated, and it may develop that statistical techniques will not prove adequate for the purpose of constructing a reliable dispersion model. It is therefore regarded as appropriate to prepare a purely physical multi-source dispersion model in parallel with the statistical modeling effort.

The physical model to be used for this purpose is that now under development by Turner (ESSA) for St. Louis. If it proves successful, this model can be adapted, with a minimum of effort, to the Chicago environment by incorporating into it the results of the hourly emission inventory and the Chicago micro-meteorological studies. To this end, the current version of the St. Louis model has been adapted for use with the Argonne IBM 360 computer system and modifications of the model to improve its performance - as applied to St. Louis - will be made during the forthcoming quarter. Most of the effort involved in the further development of the

St. Louis version of this model will be performed by Turner, with limited assistance from Argonne personnel and with the use of the Argonne computer facility.

Since the St. Louis model represents both a backup alternative in the event that statistical analysis methods prove inadequate, and a potential physical "kernel" for the refinement of a successful statistical pilot model, the effort expended on this parallel modeling study is believed to be justified.

2.4 Air Pollution Trajectory Plotting Map

In order to facilitate the dispersion analysis studies; to pinpoint the locations of major SO_2 sources and data acquisition stations; to display the significant topographical features of the Chicago metropolitan area and to define the grid network which constitutes the framework within which the dispersion model for Chicago will be developed, a large map of the city was constructed on a scale of one inch to the mile. Major SO_2 sources and data acquisition stations were plotted on this map to an accuracy of approximately one city block, and the map, permanently mounted on a display board, was equipped with a cartographic (Civil engineer's) drafting machine. By means of this machine, the range and bearing of any point on the map relative to any other point can be obtained by inspection. A master log identifying the major sources and data acquisition stations is permanently attached to the map stand.

The grid network established for the map is essentially identical to that employed by the DAPC within the confines of metropolitan Chicago; however the grid has been extended to encompass major pollution producing areas such as Gary, Indiana, Cicero, Illinois, etc. that may be expected to affect the SO_2 concentrations within the city limits. The grid also includes the arterial highway network which surrounds Chicago.

The map, drafting machine and master log are shown in fig. 2.1. It is expected that this map will be of material assistance in the visual identification of SO_2 distribution patterns and in evaluating the influence of various sources on the TAM network receptors.

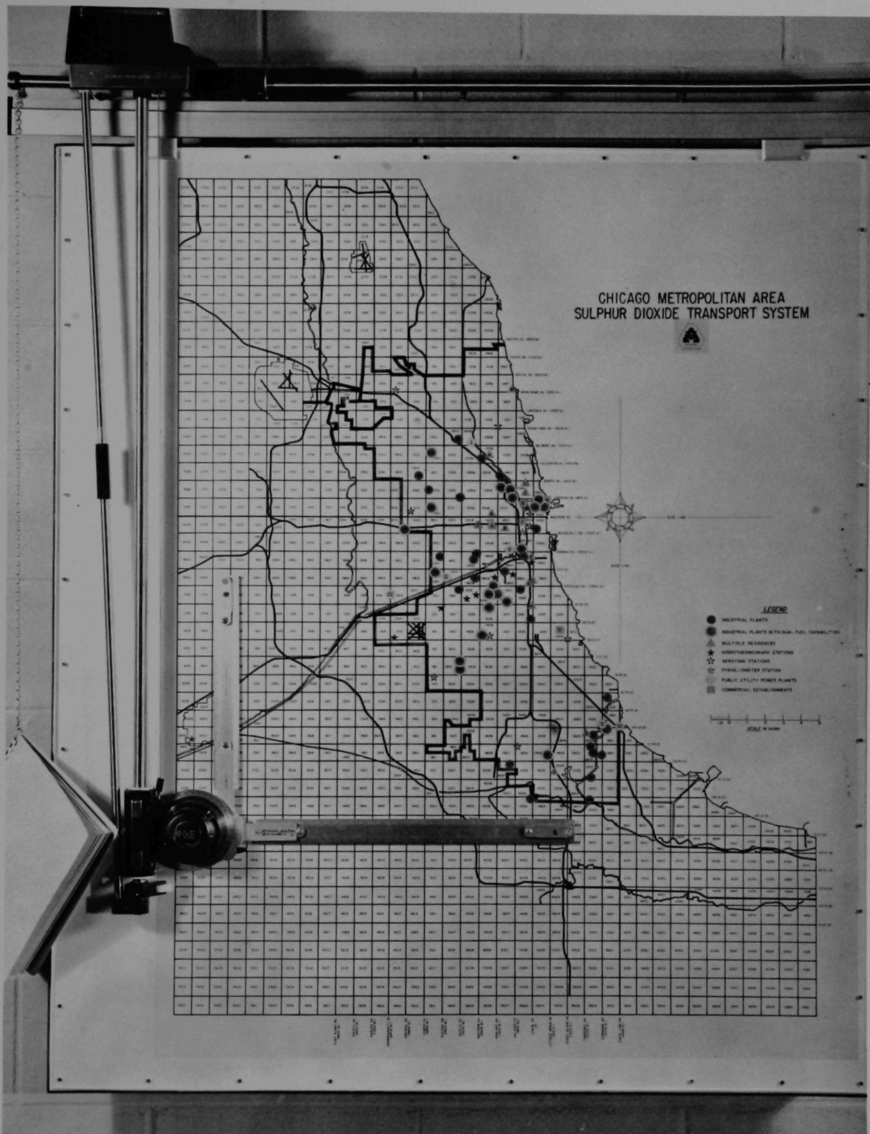

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Fig. 2.1 SO_2 Trajectory plotting map

CHICAGO AIR POLLUTION DISPERSION MODEL

3.0 Meteorology

J. Carson

3.0 Meteorology

3.1 Meteorological Factors Controlling Pollution Concentrations

Wind (speed, direction and turbulence) and atmospheric stability are the two most important meteorological factors controlling the rate at which gaseous pollutants are diluted and transported away. Sunshine, through photochemical reactions, may remove or transform certain pollutants, and precipitation may wash others out of the air. Solar and long-wave radiation and cloudiness are of importance through their influence on stability and convective turbulence.

Chicago is fortunate from the standpoint of air quality, in that the winds are usually sufficiently strong to prevent the buildup of extremely high concentrations of pollutants.

Atmospheric turbulence controls the rate at which the effluent from each source mixes with and is diluted by outside air. Observations show that turbulent eddies of all sizes, from very small (which cause plumes to widen as they entrain clean air) to very large (which cause successive portions of a given plume to meander, that is, to follow different trajectories), are operating. The large eddies are mostly the result of heating of the air from below - thermal or convective turbulence. For the given location, thermal turbulence is strongly influenced by the type, height, thickness and amount of the cloud cover, color and thermal properties of the absorbing surface as well as sunshine intensity. Smaller eddies are created by the flow of air over rough terrain - mechanical turbulence. The mechanical turbulence portion depends mostly on wind speed and terrain roughness. The intensity and spectrum of turbulence can be measured by sensitive anemometers.

Atmospheric stability, as denoted by the vertical temperature gradient, controls not only the size of the vertical and horizontal eddies but also the depth of the layer through which pollutants are mixed. Unfortunately, no measurements of this critical parameter have been or are being made over Chicago. In most city and other large scale diffusion studies, atmospheric stability (better, the diffusion coefficients which depend on stability) is estimated from meteorological data, such as time of day, cloud cover, wind speed, sunshine intensity, etc. The width of the wind direction trace is a useful index of turbulence. These techniques seem to work near the ground in areas of relatively simple terrain. These "objective stability criteria" should not be expected to apply in cities with their extreme roughness, localized heat sources, etc. Only the direct measurement of the vertical temperature profile can be expected to locate the presence, height and intensity of inversion aloft.

Whenever the temperature increases with height, vertical mixing essentially ceases. This temperature distribution is called an inversion. Ground-level inversions are created by outgoing radiation from the ground under clear or partly clear skies with weak winds at night, and are called nocturnal or radiation inversions. Pollutants released at ground level stay at that level. Pollutants released into an inversion from a tall stack or building tend to stay at the level of release, and diffuse neither upwards or downwards.

In rural areas, nocturnal inversions begin at ground level. Over urban areas, heat from streets, buildings and space heating raises the base of the inversion to a level some distance above the mean height of the roof tops. Below this surface, mechanical and thermal turbulence create unstable conditions and thorough mixing. This inversion acts as a lid to vertical diffusion and traps the smoke and other effluents below it. Since wind speeds near the ground are typically lower at night, dangerous concentrations can develop when such an inversion exists.

Since great horizontal variations in the underlying surface (height of buildings, percent of area paved, local heat sources, plant cover, etc.) and cloud cover exist over the Chicago area, variations in the height of the base and intensity of nocturnal inversions are also likely. Indeed, a strong nighttime inversion might be present in one part of the city and none in another. Low level inversions are also present over Chicago in spring and summer when air cooled from below moves into the city from Lake Michigan.

Unfortunately, no vertical temperature measurements have been taken in the City of Chicago to locate and describe these inversions.

Subsidence or sinking air in high pressure areas (anticyclones) creates inversion layers in the air some distance aloft, with bases typically 1500 to 4000 feet above the ground. This layer acts to halt vertical diffusion; high concentrations of pollutants can build up in the reduced volume of air below the "lid". Since high pressure areas usually move slowly and are accompanied by weak surface winds, dangerous levels of pollution can be created.

The only important topographic factor controlling diffusion processes in the Chicago area is Lake Michigan. This large, deep body of water changes its temperature much more slowly than does the surrounding land, and acts as a heat source or sink whenever an air mass of different temperature crosses it. When the air is warmer than the water (as in spring and summer), the air is cooled from below and made more stable. Vertical mixing in this modified air is greatly reduced. As the air moves inland, surface heating and mechanical turbulence will tend to destroy the inversion. When the temperature difference between land and water is reversed (typically in fall and early winter), the air is heated and moistened from below. Heavy snows often occur near the shore line when very cold polar air crosses the lake. The resulting instability acts to lower concentrations of pollutants due to greater depth of mixing; some of the gaseous wastes are also washed out with the precipitation.

The change in surface roughness between land and water is important in creating zones of convergence and divergence for certain wind speeds and directions. For example, with strong southwesterly flow over Chicago, the surface wind speeds are reduced more over the land than the lake. A zone of divergence and sinking air is created along the shore line.

During clear daytime hours in spring and summer, the air over the land is heated to a higher temperature than the air over the lake. If the winds over the area are light as they are near the center of an anticyclone, the relatively cold and dense air moves from the lake onto the land as a "lake breeze". Usually, the lake breeze penetrates only one or two miles inland; under ideal conditions, it can reach Argonne, 27 miles inland. Very large temperature differences, as much as 20°F, are observed. High levels of smoke and pollution are found in the convergence zone along the lake breeze front.

The air mass blowing in from the lake is clean and stable and pushes in under warmer air aloft, creating a very stable atmosphere with little mixing.

It should be noted that cool wind off the lake is not necessarily a "lake breeze". A northeast wind Chicago produced by the pressure field instead of unequal warming will have much different diffusion characteristics than the lake breeze.

3.2 Available Meteorological Data

3.2.1 Surface Weather Data

The quantity and geographical distribution of surface weather observations (wind speed and direction, air temperature cloud cover, precipitation, etc.) in the Chicago area appear to be sufficient for use in the computer model. Briefly, the sources of surface weather data are:

1) Chicago's TAM network. Wind speed and direction, averaged over 5-minute intervals, are available from each of the eight SO_2 stations every 15 minutes. Tape records of these observations for the period 1 January 1966 through 30 April 1967 have been error-checked by DAPC and supplied to Argonne. Each of these stations has been visited by an Argonne meteorologist. Seven of the eight Aerovanes are located on short (15 to 30 feet) masts on the roof of three to four story schools. The remaining wind sensor is located 40 feet above the roof of a 10-story building in the Loop. Visual examination of Aerovane motion and wind traces indicate that all of these instruments are located too close to the building itself to yield "representative" wind speed and wind direction information for that area of the city. An analysis of the data must be made to determine their usefulness. It is possible that certain directions at a given site are good, while other directions are invalid. Pen-and-ink traces of the wind have been taken and the strip charts stored. The width of the wind direction trace can be read from these charts, if desired, to give an index of standard deviation of wind direction.

2) Airport data. The standard hourly weather observations are made at four airports in the Chicago area: Meigs, Midway, O'Hare International and Glenview Naval Air Station. The Midway and

Glenview data are available hourly on punched cards; only three-hourly data are available on tape for O'Hare. Tapes containing these data have been received from the National Weather Records Center. None of the Meigs data has been placed on cards. Copies of the WBAN-10 weather records for this station have been received; these data will be punched at Argonne. The Meigs weather station is manned from about 0500 CST to about 2200 or 2300 CST only.

3) DAPC Hygrothermograph and Sunshine Data. The City maintains a nine-station network of hygrothermographs to determine the inland penetration of lake breezes. These stations extend along a line essentially parallel to the Stevenson Expressway. Hourly sunshine values are available from a pyranometer located near Chicago's loop and can be compared with a similar instrument at Argonne, outside of the city.

4) Argonne Meteorological Data. The meteorological data collected at Argonne National Laboratory will be used in this study. This observing station was specifically designed to measure those parameters controlling diffusion: atmospheric stability, wind speed and direction at five levels up to 150 feet, net and solar radiation, etc. These are the only stability records available in the Chicago area. Unfortunately, the data are for a shallow (up to 144 feet above ground) layer and are taken in an open, grass covered field; it is not yet clear that these data can be effectively related to the urban environment of the city.

3.2.2 Upper Air Data

A real understanding of the transport and diffusion mechanisms over the City of Chicago would require frequent measurements of temperature, wind speed and wind direction up to the top of the mixing layer at several locations. These observations would give the time and space variations of stability, wind field, height of the mixing layer, and the depth of penetration and thickness of the lake breeze. The data would also show the height, thickness and horizontal extent of inversion layers aloft. At the present time, the only vertical profile data in the Chicago area are those collected from the relatively short, rural Argonne stack.

The nearest location at which radiosonde observations are made is the U. S. Weather Bureau RAWIN station at Peoria, Illinois, 135 miles Southwest of Chicago. Four flights are made daily. The Weather Bureau maintains four pilot balloon or winds-aloft stations in the area; Moline, Illinois; Madison, Wisconsin; Fort Wayne, Indiana; and Muskegon, Michigan. The Peoria RAWIN data, which contain wind as well as temperature and humidity observations, have been received from N.W.R.C. at Asheville.

3.3 Vertical Sounding Proposals

3.3.1 The Need for Temperature Profile Observations

The most serious gap in our understanding of diffusion processes in Chicago is the complete lack of wind and temperature profile observations in the critical zone of mixing and transport over the city. Extrapolation of the RAWIN and pilot balloon data to Chicago is not possible. In order to specify current transport and dilution patterns, and to predict future air pollution concentrations, urban atmospheric stability and inversion layer behavior must be known and related to synoptic weather patterns.

This lack of upper air data might be overcome by the use of a set of "objective stability criteria", similar to those used by Pasquill in England, Turner at Nashville and St. Louis, and Koogler at Jacksonville, Florida.

Pasquill's diffusion parameters, σ_x and σ_y, were developed in a series of diffusion experiment in rural areas, and have been shown to be reasonably valid for this type of terrain. Similar experiments over large cities have not been conducted and valid sigmas for this type of terrain, with their roughness and "heat island" effects, are not available. Because of Lake Michigan, large horizontal variations wind direction and stability are often found over Chicago. Under these conditions, more than one set of diffusion parameters would be needed to compute diffusion patterns.

A statistical regression analysis could be used to derive the diffusion coefficients from receptor and emission data for typical weather conditions. The derived coefficients would thus reflect the city's roughness, heat island effect, inversion layers and stability.

3.3.2 Direct Observational Methods

The following observational programs have been suggested to supply the data needed to specify the temperature and/or wind fields in the mixing layer over Chicago:

1) Temperature and sulfur dioxide sensors on a helicopter.
2) Temperature sensors on towers and/or tall buildings.
3) Frequent flights of slow-rising radiosondes or similar balloons.
4) Zero-lift balloons flights (wind data only).
5) Indirect probes, such as LIDAR or infrared techniques.
6) A series of tracer experiments

The first three items will be discussed in following sections.

Helicopter program. Helicopter-mounted sensors have been successfully used by Davidson in New York City and by Thomas of the TVA to measure vertical temperature and sulfur dioxide profiles.

The DAPC is considering the purchase of a similar instrument package and plans to fly the equipment on a Chicago Fire Department helicopter. It is expected that this equipment will be used to measure temperature and pollution patterns over the city for a number of typical weather situations, rather than for a program continuous observations. These typical situations will then be studied in detail to deduce diffusion mechanisms.

Experience in New York City has shown that helicopter-mounted sensors can cover a large area rapidly and at moderate cost under most weather conditions.

Towers and Tall Buildings. It is not possible to make continuous upper level measurements using balloons, helicopters or airplanes.

Meteorologists have used towers to measure vertical wind and temperature profile for decades. These towers do not have internal heat sources but do influence the wind somewhat. Koogler used an instrumented TV tower in downtown Jacksonville, Florida for stability measurements. Several very tall towers would be needed in Chicago, and none are available.

It has been suggested that the Hancock Building, which will be 1105 feet tall with two TV masts extending another 400 feet and which is now under construction, be used to mount temperature sensors.

One possible configuration would be four sensors at various heights or each corner of the building. A windvane on the roof would be part of the circuit so that only the upwind sensors would be recorded. A meeting with the architects of the building to discuss problems associated with the system is scheduled.

It is not known whether a tall building can be used to measure vertical temperature profiles, due both to the turbulence created by the building and to the heat escaping from the structure itself. Booms much longer than ten feet may be needed to escape the thermal boundary layer. One temperature sensor located at the top of the TV tower, plus another nearer the ground but away from building heat, may produce better stability data than a series of sensors along the corners.

Balloon Soundings. Personnel and cost factors make balloon programs most unattractive. Several flights per day would be needed to specify the time variability of lapse rate at one site, and several sites would be needed to describe the horizontal variations of stability, etc. Hazards to aircraft would probably prevent the use of the standard radiosonde system so near the Chicago airports. Zero-lift balloons, such as the Tetroon, provide wind speed and direction as well as trajectory data, but no vertical temperature information.

Indirect Sensing. Several techniques for exploring the surface boundary layer using ground-based sensors are being developed and tested; at the present time, none of these is sufficiently reliable or available for a routine observational program.

Tracer Experiments. Information on diffusion rates under various weather conditions from a single source in an urban complex such as Chicago is needed. It has been suggested that a series of field studies, using sulfur hexaflouride (SF_6) as the tracer, be conducted. The feasibility of conducting these experiments is being investigated.

one possible configuration would be that sensors at various heights be on one corner of the building. A discussion on the roof [illegible] part of the circuit so that only the [illegible] recorded. A meeting with the architect [illegible] problems associated with the system of [illegible].

It is not known whether a tall building [illegible] measure vertical temperature profiles [illegible] because the [illegible] created by the building and by the heat escaping from the building itself. Above much [illegible] than the building [illegible] the thermal boundary layer. The temperature [illegible] at the top of the TV tower, plus another near the ground [illegible] heat, may provide [illegible] along the coast.

Balloon Soundings. [illegible] Several [illegible] would be needed to specify the time variability of [illegible] and several sites would be needed to describe the horizontal variations of stability, etc. Hazards to aircraft would probably prevent the use of the standard [illegible] Chicago airports. Man-lift balloons, [illegible] provide wind speed and direction as well as trajectory data but not vertical temperature information.

Indirect Sensing. Several techniques for measuring the boundary layer using ground-based sensors are being developed [illegible] at the present time, none of these is [illegible] or available for a routine [illegible] program.

Tracer Experiments. Information of diffusion rates [illegible] and weather conditions from a single source in an urban area [illegible] is needed. It has been suggested that [illegible] (SF_6) [illegible]. The feasibility of conducting these experiments is being investigated.

CHICAGO AIR POLLUTION DISPERSION MODEL

4.0 Emission Inventory

E. Croke

J. Roberts

4.0 Emission Inventory

One of the major tasks in the development of the Chicago air pollution dispersion model is the acquisition of SO_2 emission data for the city. The progress of the effort mounted to accumulate this data is described in this section. Figure 4.1 summarizes the emission inventory study and indicates the major sources of data.

4.1 Time Scale

Since the dispersion model must be designed to yield air quality forecasts on a time scale of six to forty-eight hours in order to serve as a useful prediction tool, it was evident that the maximum period over which time variant emissions could be averaged for input to the model would, in general, be six hours. The minimum meaningful time period for which SO_2 emissions could be averaged was dictated by the fact that the DAPC air quality monitoring system yields five-minute averaged wind and air quality data at fifteen minute intervals.

The decision to seek emission data averaged over one-hour periods was, in the end, predicated on the manifest impossibility ofobtaining meaningful emission data on any shorter time scale, and by the fact that the Weather Bureau meteorological records which represent an essential component of the model are, in general, based on hourly data or hourly averaged data. An additional consideration of practical importance was associated with the fact that the magnitude of the task of processing emission data from those sources for which accurate continuous fuel consumption records are kept would be altogether excessive if emission data averaged on a shorter time scale than one hour were sought.

4.2 Fuel Types

The identification of the fuels that would be associated with SO_2 production presented no significant problem, since essentially all of the SO_2 sources in Chicago burn southern Illinois or Kentucky coal or one of several grades of fuel oil. No other energy source used in the area, e.g. natural gas, automotive or aviation gasoline, etc., contains enough sulfur to constitute a

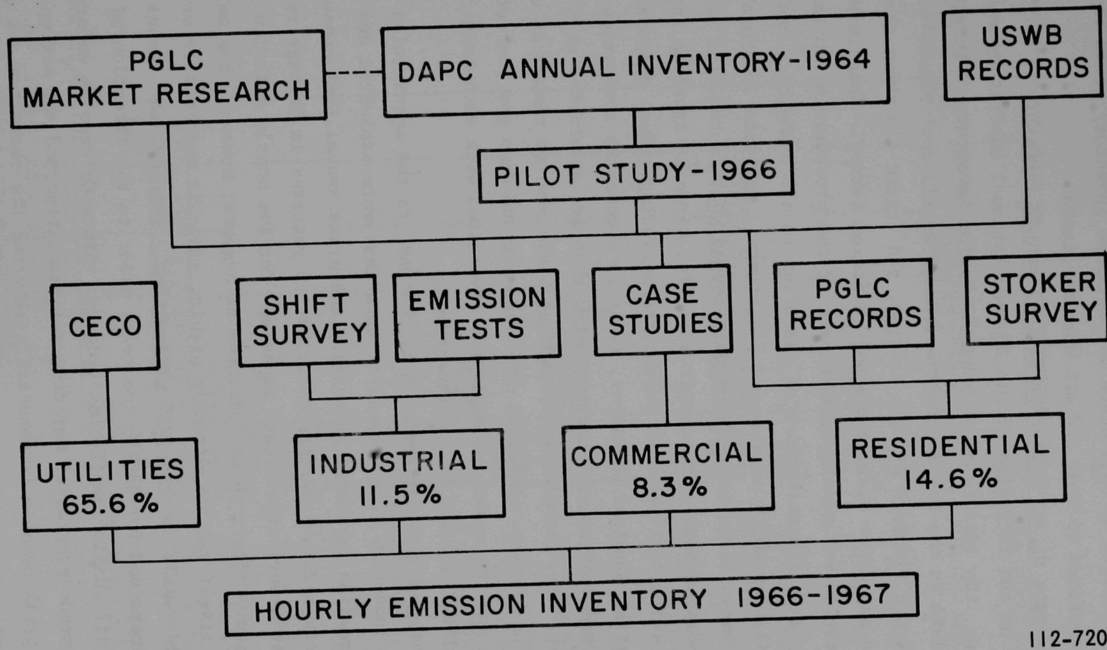


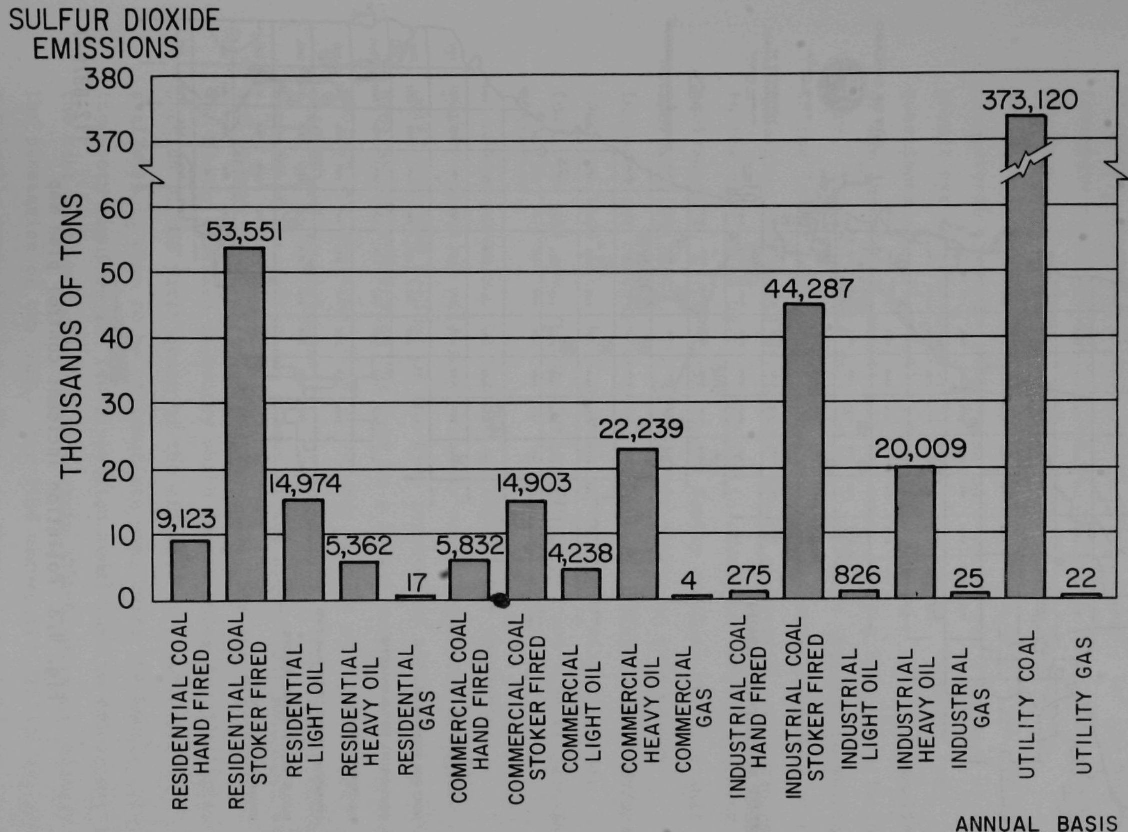
Fig. 4.1 SO_2 Emission inventory

major source of SO_2, hence the emission inventory could legitimately be confined to coal and oil burning plants.

4.3 Deparment of Air Pollution Control Annual Inventory

At the inception of the Argonne National Laboratory pollution study, the results of an annual emission inventory program conducted in 1964 by the Chicago DAPC were made available. Figure 4.2 summarizes the findings of this program, and figure 4.3 shows the city grid map which defined the DAPC emission survey. This inventory operation was developed as a part of the procedure by which the city issues certificates of operation to all commercial and industrial facilities which produce air pollutants. The data accumulated in the emission inventory goes well beyond what is required for the SO_2 dispersion model, in certain respects, since it involves information concerning all types of pollutants, including refuse disposal products, volatile chemical emissions, types of processing activities, number and types of ovens, furnaces, etc. that are associated with a given plant. The inventory also indicates the average number of operating shifts per day, number of days per week and days per year of operation and the number of employees associated with each industrial facility included in the inventory.

The methodology employed by the DAPC in the acquisition of this inventory, the sources of data that were exploited and the information developed concerning the gross annual fuel consumption pattern and fuel burning distribution patterns in Chicago represented a very significant advantage for the hourly emission inventory effort to be conducted at Argonne; however, the emission data itself was not directly usable, since it was totally oriented toward yearly average fuel consumption. Further, the annual data were obtained for 1964 - two years prior to the inception of the DAPC air quality monitoring program. Since Chicago is undergoing a vigorous program of building and demolition and the metropolitan industrial complex is constantly altering its character and distribution pattern, it was concluded that emission data concurrent with the time period within which the air quality and meteorological data were obtained would be esential to the success of the modeling effort.



112-7209

Fig. 4.2 Sulfur dioxide sources

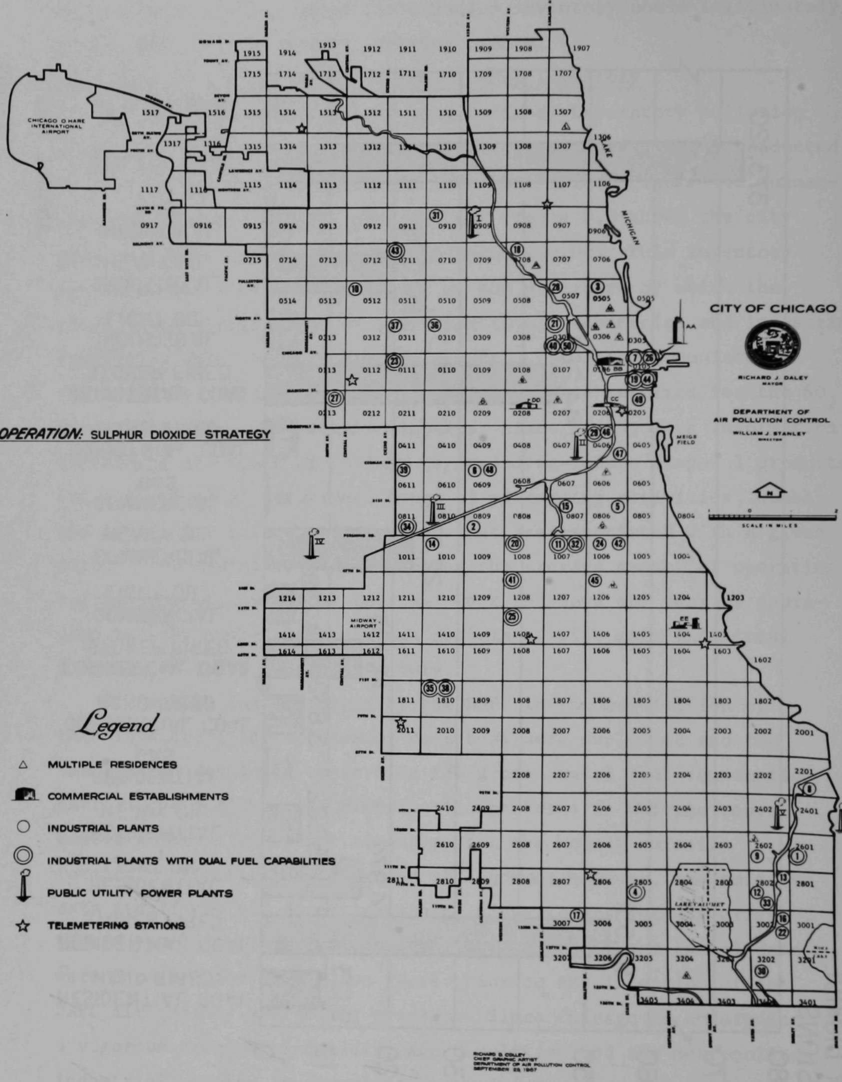


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Fig. 4.3 Pollution incident control plan map

An updated annual emission inventory which reflected the magnitudes and distribution of fuel burning patterns for 1966-67 would, of course, represent a most useful starting point for the hourly inventory - particularly in the context of the highly detailed square-mile breakdown of source strengths and types of SO_2 emitters sought by the DAPC. Such an updating effort was, in fact, inaugurated early in 1966 by the DAPC within the framework of the permit system administered by that department. Computer card questionnaires (fig. 4.4) were distributed to a selected sampling of the industrial, commercial and space heating fuel users in the city. The results of this "pilot study" were employed to initiate, in the latter part of 1967, a far more comprehensive survey of the same kind that would ultimately include essentially all furnaces in the city which have a capacity in excess of 288,000 BTU/hour - equivalent to a very large single family dwelling or a 2-4 unit apartment building. The information sought in this survey included the categorization of sources according to the standard land use code (fig. 4.5) as well as by square mile location, fuel type and use, refuse burning practices, and type of process operation.

Unfortunately, the results of this rather comprehensive survey operation will very probably not be available in usable form until mid-1968 because of the time involved in administering the program and processing the data in a format amenable to computerized storage and sorting. This survey may thus be of considerable utility and significance for the economic and long-range planning aspects of the latter two phases of the Argonne air pollution study and it may, in addition, prove invaluable for the refinement of the hourly emission inventory which is scheduled for the latter portion of the first phase of the effort, but it will not be available in time to be of immediate use; hence the hourly emission inventory required for the dispersion model must be developed, for the most part, by accumulating certain 1966-67 data not already in the possession of the DAPC. The 1964 survey did, of course, prove a valuable asset for this effort, in that it identified the location, 1

CITY OF CHICAGO
DEPARTMENT OF AIR POLLUTION CONTROL
320 N. CLARK STREET
CHICAGO, ILL. 60610

RICHARD J. DALEY, MAYOR — WILLIAM J. STANLEY, DIRECTOR

BUILDING DATA

Prepared by:
(Name)
(Date) (Telephone No.)

Our records show that you are the owner or agent for the property located at:

Please complete this and all additional enclosed cards and return in the enclosed envelope

WITHIN 10 DAYS

ISC 32449

BUILDING CLASSIFICATION
(Complete applicable boxes)

Manufacturing	–	Sq.Ft.Total Floor Area
Commercial	–	Sq.Ft.Total Floor Area
Residential	–	No. of Dwelling Units

2

CITY OF CHICAGO
DEPARTMENT OF AIR POLLUTION CONTROL
320 N. CLARK STREET
CHICAGO, ILL. 60610

RICHARD J. DALEY, MAYOR — WILLIAM J. STANLEY, DIRECTOR

BOILER/BURNER DATA

OUR RECORDS SHOW THIS DEVICE INSTALLED IN YOUR BLDG. ______ (BOILER) ______ (BURNER)

FUEL USED FOR THIS DEVICE	QUANTITY OF FUEL USED FROM JAN. 1, 1966 - DEC. 31, 1966		
( ) COAL ( ) OIL ( ) GAS		( ) TONS ( ) GALLONS ( ) CUBIC FT.	$ COST-WHOLE AMT.

IF COAL: WHAT SOURCE AREA? ILL. ( ) E. KY. ( ) W. KY. ( ) IND. ( ) OHIO ( ) W. VA. ( ) PENN. ( )

WHAT TYPE BURNING UNIT? UNDERFEED ( ) SPREADER ( ) CYCLONE ( ) HAND FIRED ( ) PULVERIZED COAL ( )

IF OIL: WHAT GRADE? #1( ) #2( ) #3( ) #4( ) #5( ) #6( )

ISC 32450

3

CITY OF CHICAGO
DEPARTMENT OF AIR POLLUTION CONTROL
320 N. CLARK STREET
CHICAGO, ILL. 60610

RICHARD J. DALEY, MAYOR — WILLIAM J. STANLEY, DIRECTOR

REFUSE DATA

Our records show this incinerator installed in your bldg. ______

1. Is incinerator used? ☐ YES ☐ NO
2. Is it gas fired? ☐ YES ☐ NO
3. Is it flue-fed? ☐ YES ☐ NO
4. What is the principle type of refuse burning unit used?
   ☐ Coal Boiler ☐ Other Boiler ☐ 55 gal. Drum ☐ Single Chamber Incinerator ☐ Multiple Chamber Incinerator
5. What is the MAIN type of refuse burned in this unit? (check ONE box only)
   ☐ Rubbish (dry cartons, paper) ☐ Rubbish & Garbage (even mixture) ☐ Garbage ☐ Animal or Human Remains ☐ Semi-solid Industrial Mat'l. ☐ Solid Industrial Mat'l.
6. How many 55 gal. drums of refuse are generated per month? ______ How many 55 gal. drums burned in this device? ______

ISC 32513

4

CITY OF CHICAGO
320 N. CLARK STREET
CHICAGO, ILL. 60610

RICHARD J. DALEY, MAYOR — WILLIAM J. STANLEY, DIRECTOR

COMMERCIAL BUILDING CLASSIFICATION

TRANSPORTATION, COMMUNICATION, UTILITIES
- ☐ 1. Railroad, rapid rail transit, and street railway
- ☐ 2. Motor vehicle
- ☐ 3. Aircraft
- ☐ 4. Marine craft
- ☐ 5. Highway and street right-of-way
- ☐ 6. Automobile parking
- ☐ 7. Communication
- ☐ 8. Utilities
- ☐ 9. Other—reservation, forwarding, control stations, services, etc.

SERVICES
- ☐ 1. Finance, insurance, and real estate
- ☐ 2. Personal
- ☐ 3. Business
- ☐ 4. Repair
- ☐ 5. Professional
- ☐ 6. Contract construction
- ☐ 7. Governmental
- ☐ 8. Education
- ☐ 9. Other—religious, charitable, welfare, etc.

TRADE
- ☐ 1. Wholesale trade
- ☐ 2. Retail trade—building materials, hardware, farm equip.
- ☐ 3. Retail trade—general merchandise
- ☐ 4. Retail trade—food
- ☐ 5. Retail trade—automotive, marine craft, aircraft & access.
- ☐ 6. Retail trade—apparel and accessories
- ☐ 7. Retail trade—furniture, home furnishings and equipment
- ☐ 8. Retail trade—eating and drinking gifts, etc.

CULTURAL, ENTERTAINMENT, AND RECREATIONAL
- ☐ 1. Cultural activities and natural exhibitions
- ☐ 2. Public assembly
- ☐ 3. Amusements
- ☐ 4. Recreational activities
- ☐ 5. Resorts and group camps
- ☐ 6. Parks
- ☐ 9. Other

(CHECK ALL APPLICABLE BOXES)

ISC 32514

5

CITY OF CHICAGO
DEPARTMENT OF AIR POLLUTION CONTROL
320 N. CLARK STREET
CHICAGO, ILL. 60610

RICHARD J. DALEY, MAYOR — WILLIAM J. STANLEY, DIRECTOR

RESIDENTIAL BUILDING CLASSIFICATION

HOUSEHOLD
- ☐ HOUSEHOLD UNITS (APARTMENTS, HOMES, ETC.)

GROUP QUARTERS
- ☐ ROOMING AND BOARDING HOUSES (5 OR MORE BOARDERS)
- ☐ FRATERNITY AND SORORITY HOUSES
- ☐ OTHER MEMBERSHIP LODGINGS
- ☐ NURSES HOMES
- ☐ COLLEGE DORMITORIES
- ☐ OTHER MEMBERSHIP HALLS OR DORMITORIES
- ☐ RETIREMENT HOMES
- ☐ ORPHANAGES
- ☐ CONVENTS
- ☐ RECTORIES
- ☐ OTHER RELIGIOUS QUARTERS
- ☐ OTHER GROUP QUARTERS

RESIDENTIAL HOTELS
- ☐ RESIDENTIAL HOTELS (SEVENTY FIVE PERCENT OR MORE OCCUPIED BY GUESTS WHO RESIDE MORE THAN 30 DAYS)

TRANSIENT LODGINGS
- ☐ HOTELS, TOURIST COURTS, AND MOTELS (LESS THAN SEVENTY FIVE PERCENT OCCUPIED BY GUESTS WHO RESIDE MORE THAN 30 DAYS)
- ☐ OTHER TRANSIENT LODGING (LESS THAN SEVENTY FIVE PERCENT OCCUPIED BY GUESTS WHO RESIDE LESS THAN 30 DAYS AND LESS THAN FIFTY PERCENT OF SPACE USED FOR ASSOCIATED ACTIVITIES—AS WITH Y.M.C.A., Y.W.C.A., AND Y.M.H.A. WITH LIVING QUARTERS)

ISC 32515

Fig. 4.4 1966-67 emission survey data cards

BASIC ACTIVITY CODE

CODE	CATEGORY
1	RESIDENTIAL
2 AND 3	MANUFACTURING
4	TRANSPORTATION, COMMUNICATION AND UTILITIES
5	TRADE
6	SERVICES
7	CULTURAL, INTERTAINMENT, AND RECREATIONAL
8	RESOURCE PRODUCTION AND EXTRACTION
9	UNDEVELOPED LAND AND WATER AREAS

AUXILIARY CODE

CODE	CATEGORY
0	NOT AN AUXILIARY
1	CENTRAL OR ADMINISTRATIVE OFFICE
2	SALES OFFICE
3	RESEARCH AND DEVELOPMENT
4	WAREHOUSING AND STORAGE
5	AUTOMOBILE PARKING
6	MOTOR VEHICLE GARAGE (MAINTENANCE AND/OR STORAGE OF VEHICLES)
7	STEAM AND POWER PLANT
8 AND 9	(OPEN CODES)

OWNERSHIP CODE

CODE	CATEGORY
1	PUBLIC
	11 FEDERAL
	12 STATE
	13 COUNTY
	14 TOWNSHIP
	15 MUNICIPAL
	16 SPECIAL DISTRICT
	19 OTHER PUBLIC, NEC
2	PRIVATE
	20 PRIVATE

STRUCTURE CODE

CODE	CATEGORY
1	SINGLE FAMILY STRUCTURES
	11 SINGLE UNITS-DETACHED
	12 SINGLE UNITS-SEMIATTACHED
	13 SINGLE UNITS-ATTACHED ROW
2	TWO FAMILY STRUCTURES
	21 TWO UNITS-SIDE BY SIDE
	22 TWO UNITS-ONE ABOVE THE OTHER
3	MULTIFAMILY STRUCTURES
	31 APARTMENTS-WALK UP
	32 APARTMENTS-ELEVATOR
4	CONVERTED STRUCTURES
	41 CONVERTED FROM-DETACHED
	42 CONVERTED FROM-SEMIATTACHED
	43 CONVERTED FROM-ATTACHED ROW
5	MOBILE HOMES
	51 MOBILE HOMES-ON PERMANENT FOUNDATION
	MOBILE HOMES-NOT ON PERMANENT FOUNDATION
6	NONRESIDENTIAL STRUCTURES
	90 NONRESIDENTIAL STRUCTURES

NUMBER OF HOUSEHOLD UNITS

NUMBER OF DWELLING UNITS FOR RESIDENTIAL BUILDINGS

OR

FLOOR AREA FOR COMMERCIAL AND INDUSTRIAL BUILDINGS

112-7211

Fig. 4.5 Standard land use code

nature and relative magnitudes of most of the major SO_2 sources in the city, and yielded useful qualitative information about the character of Chicago as a pollution producing entity.

4.4 Argonne Hourly Emission Inventory

It was evident from the 1964 emission inventory that the SO_2 sources in the city fall into four distinct categories. These are:

1) Power generating stations
2) Industrial plants
3) Residential buildings
4) Commercial structures

The fuel burning schedule of each of these source types is dependent on different operating factors, and the sources of information and techniques associated with the acqusition of hourly emission data are essentially unique to each type.

4.4.1 Power Generating Stations

The Commonwealth Edison Company (CECO) operates six major coal burning power plants within, or immediately adjacent to, Chicago. In the aggregate, and on an annual basis, these six generating stations account for 65.6% of the total SO_2 emissions in the city. In the order of their significance as SO_2 sources, these plants may be listed as follows:

Plant Designation	SO_2 tons per year	SO_2 percent of City Total
Crawford	107,954	18.97
Ridgeland	100,540	17.67
Fisk	73,438	12.90
State Line	70,606	12.42
Northwest	10,566	1.86
Calumet	10,016	1.76
	373,120 Tons	65.58%

Because of the predominance of these six sources in the SO_2 emission pattern, it was evident that major emphasis should be placed on obtaining the most accurate and detailed record of their emission history that is compatible with the schedule of the SO_2 dispersion modeling program. An investigation of the CECO operating procedures revealed that continuous (circular chart) records of power production are maintained for each generating unit of each power plant, and that daily and monthly coal consumption and coal sulfur content records are available for the aggregate of boilers that serves each generating unit in each plant. Sufficient information is therefore available to relate the hourly average coal consumed by all boilers which supply a given generating unit with the hourly average power produced by that unit. Daily average coal sulfur content records may be combined with the calculated hourly coal consumption to yield hourly SO_2 emission.

The number of boilers which serve a given generator at a given time are known, however it is not possible to distinguish one boiler from another by means of this data, hence it is necessary to assume that all operating boilers which serve a generator at a given time are equally loaded. The geometry of the stacks which serve the boilers associated with each generator is known, and the stack exit temperatures may be obtained, approximately, by means of a set of curves of stack temperature vs. power load (see fig. 4.6) which have been provided by CECO. The most important gap in this otherwise essentially complete record is therefore associated with the fact that stack exit velocities must be approximated because each stack serving a given generator is assumed to be equally loaded. This approximation is considered to be acceptable for the purposes of calculating smoke plume rise, since the uncertainty associated with the accuracy of the velocity relationship in various plume rise correlations almost certainly outweighs the errors involved in accepting an approximation of stack exit velocity.

The processing of CECO emission data is complicated by the fact that certain of the larger plants are equipped to burn natural gas (on an interruptible basis) in place of coal. On occasion, during spring and fall and during a few moderate periods in winter, therefore, certain of the CECO plants may switch from coal to gas and back - depending on the amount of gas made available by the supplier. During the summer months, moreover, when low gas rates prevail, the dual fuel CECO plants operate almost entirely on gas excepting for a nominal (about 15%) coal input required to maintain

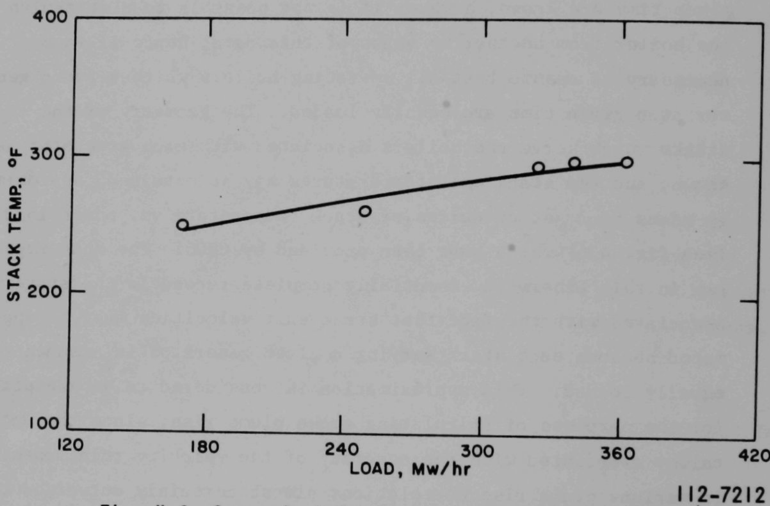


Fig. 4.6 Ceco stack temperature vs power load

a protective slag coating on the boiler feed grates. In order to separate the coal-produced power from the gas-produced power, hourly gas consumption records were made available which, when combined with the data inventory described above yield hourly coal consumption data for dual fuel operating periods. The stack emission factor of 36.8S (where S = percent sulfur content) pounds SO_2 per ton of coal is used to convert the CECO fuel consumption to equivalent SO_2 emission.

Despite the excellent record-keeping policies of CECO, the task of acquiring raw data from each plant and rendering it into a form suitable for computer data processing is lengthy and time consuming. The raw data acquisition effort began at the Fisk Plant in mid-December 1967, and approximately one man-month was required to extract the required data from CECO records for that plant. At this rate, it is expected that the inventory of all six CECO plants will be completed by the end of March 1968, however, as noted in section 2.0 of this report, it is not necessary to await the completion of the CECO inventory to begin the statistical SO_2 dispersion studies, hence, the rate of acquisition of CECO data will not pace the remainder of the program.

The reduction and processing of the CECO data will be performed at Argonne. The computer codes required to process the raw data, store the emission information and load the master emission data file are now in preparation. Data from the Fisk plant will be available in processed form by January 31, 1968 and the initial statistical analysis experiments will begin at that time.

4.4.2 <u>Industrial SO_2 Sources</u>

Approximately 2500 coal and oil burning industrial plants of all sizes and types account for approximately 12% of the total annual SO_2 emission in Chicago. The fuel burned by most of these plants is used for both space heating and processing operations and, in some cases, to power steam air conditioning equipment used during the summer months. Many of the larger industrial plants are equipped to burn either gas or coal and, like the utility plants, are "interruptible" customers of the local gas supplier. Such plants tend to burn gas during the nonheating season when this fuel is obtainable at low rates.

To obtain a detailed hourly emission inventory for all of these industrial plants for a two-year period would involve a prohibitively large expenditure of time and manpower. Moreover, only the largest industrial facilities have been found to maintain fuel consumption records of the kind required to yield hourly emission data. It was evident, therefore, that the inventory of industrial SO_2 sources would require the acceptance of certain approximations if the task was to be completed in the requisite time and with the available manpower.

On the basis of the 1964 DAPC annual inventory, it was found that 100 of the largest industrial SO_2 producers account for about 9.5% of the total annual emission. It was therefore concluded that the industrial emission inventory could be confined to these major sources, which account for approximately 83% of all industrial emissions. A survey of the major industrial plants in this category revealed that many do not retain hourly steam flow records or any other data by which hourly fuel consumption could be calculated. Most of these plants do keep monthly fuel purchase records and many maintain daily boiler log sheets. Certain plants follow a practice of disposing of all log sheet data after three months, while other retain complete records for several years. From this aggregate of disparate data it was necessary to develop a consistent scheme for obtaining hourly emission information.

To obtain accurate hourly fuel burn data for those plants which do retain continuous steam flow records, etc., would have involved an expenditure of time and effort that was altogether out of proportion to the information yield. The largest fuel burning industrial plant in the city accounts for only 0.83% of the annual SO_2 total, yet the time expended to reduce emission data for that plant (about one man-month) would have been essentially identical to that required for a utility plant which produces over 10% of the annual total. To obtain detailed hourly data for even a few of the major plants that do keep appropriate records is therefore well beyond the capacity of the manpower and time resources available for the program.

As a realistic compromise between the requirement for hourly fuel burn data on the one hand and the combination of incomplete records and/or excessive data reduction time on the other, it was concluded that industrial emissions would be sought on the basis of a working shift time scale - that is, in eight hour averaged increments.

Shift Inventory Methodology

To obtain shift-oriented emission data, three sources of information were exploited. Firstly, a questionnaire form was developed by the DAPC (Appendix II) which was intended to establish the number of shifts actually worked by a given plant during 1966-67, the plant shutdown periods and holidays, the fuel burning load distribution among shifts, the startup and shutdown transient times, the distribution of fuel consumption between space heating and processing and, of course, the type of fuel used and its sulfur content.

Secondly, for those plants which retain appropriate records, copies of the fuel use log sheets for the sample month of December 1966 and for twelve selected zero-degree (nonheating) weekdays in 1966-67 were obtained. For those plants which retain hourly steam records but lack fuel log records, steam charts were sought on the premise that these could be used to approximate the quantities of fuel used to produce the steam - on a shift basis. This information will serve as normalizing data to validate the fuel use trend patterns established via the questionnaire, and will aid in the separation of base, processing and space-heating fuel burning loads for each plant.

Thirdly, fuel consumption and emission data acquired during a series of emission monitoring and control tests planned by Argonne and the DAPC and administered by the latter are available for the month of October 1967. This data, accumulated for the 50 largest industrial (and commercial) SO_2 sources in the city, are, for the most part, in the form of hourly or daily fuel consumption and SO_2 emission records for each source. Some of the data is in excellent form but much is incomplete, hence this information is primarily of value in serving as an additional trend validating record for those plants for which it is available.

It is fairly evident that the acquisition of shift-oriented emission data rather than hourly data is the only realistic approach to the industrial inventory problem; considering the available manpower and program schedule, but it is, of course, legitimate to consider whether such data would suffice for the purposes of constructing a statistical dispersion model. In general, shift data will suffice, it is believed, provided that the process heat load for a plant can be separated from the requirements for space heating. In this case, it is found that for any given shift, the process load tends to be essentially constant, while the space heating load varies with hourly changes in the heating demand. The latter portion of the total shift load can be processed to yield hourly data by means of the same hourly space heating correlation employed for large residential and commercial structures (described subsequently in this report). An exception to this rule is, of course, encountered with those plants which follow a practice of using waste process heat for space heating. On nonheating days this waste heat is rejected to the atmosphere. For these plants, the total hourly fuel use during a given shift tends to be essentially constant, hence it is a reasonably good approximation to assume that the shift average fuel burn can be evenly distributed over the eight hours of the shift.

Shift Survey Pilot Study

The scheduling of the industrial data acquisition effort is influenced primarily by the requirements of the Hyde Park pilot study which represents the initial test vehicle for the statistical technique described in section 2.0 of this report. Data for those major plants in the immediate vicinity (within a six mile radius) of the Hyde Park TAM station was required in order to initiate the statistical studies for that station. Moreover, it was necessary to test the efficacy of the questionnaire - data log scheme prior to using it for the entire city-wide complex of 100 major plants.

In consequence, a pilot survey of the twelve major plants within the Hyde Park sphere of the influence was initiated. The results of this survey would reveal deficiencies in the questionnaire, provide an indication of the quality of data and the degree of response that could be expected from the survey and yield an estimate of the time required to accumulate data on all 100 of the major industrial sources. At the time of this report, this pilot survey was about 50% complete and it is expected that all data for the "Hyde Park" plants will be available by the end of January. On the basis of the results achieved to data, it is anticipated that the survey of all 100 sources will be completed by the end of the third quarter of FY 1968. Deficiencies in the questionnaire form prepared by the DAPC have been identified and a revised version of this form is in preparation.

Data processing computer programs which will reduce the raw plant data to SO_2 emissions and store the latter in the master emission file are now in preparation.

4.4.3 Residential Buildings

SO_2 emissions from residential buildings of all sizes accounts for about 14.5% of the annual total for the city. The fuel burned in these structures is, of course, almost entirely employed for space-heating purposes and is therefore highly sensitive to meteorological conditions. Superimposed on the temperature - sensitive space heating load is a more or less constant base load which is associated with ancillary fuel uses such as hot water heating, "hold fire" procedures, etc. In certain cases, steam air conditioners produce a "coolant fuel load" in large multi-unit residential structures.

In general, residential SO_2 sources may be divided into two distinct classes: Large multi-family units which are equipped with high pressure steam boilers, and small apartments or single family residences with low pressure heating units. The fuel use patterns associated with these two classes tend to differ markedly.

High Pressure Steam Plants

Very large steam-heated structures such as those operated by the Chicago Housing Authority may include many hundreds of dwelling units heated by a single, multi-boiler, central high pressure steam plant. Such plants may be coal or oil fueled, but are almost always automatically stoked. Steam pressure is maintained at demand level 24 hours per day, and the occupants of individual dwelling units adjust the temperature of their apartments by manually regulating radiator steam valves or opening windows.

The largest residential SO_2 emission source in Chicago is a multi-building apartment complex operated by the Chicago Housing Authority (CHA). The central steam plant associated with this complex accounts for about 0.1% of the total annual SO_2 emissions in the city. As shown in (Appendix I), other CHA apartments are among the major residential sources, but taken together, these relatively few, extremely large apartment complexes account for only about 0.5% of the total annual SO_2 emissions, hence it was clearly not appropriate to treat these large heating plants individually for the purposes of the hourly emission inventory. Instead, it was necessary to seek a heating pattern for buildings in this class which could be used in conjunction with hourly meteorological data and gross fuel consumption data to obtain hourly fuel burn figures for all large coal or oil fired residential structures.

It was found that three of the CHA complexes as well as the Illinois Institute of Technology complex lay within the six mile radius "sphere of influence" of the Hyde Park station, hence these were chosen as samples of their class and 1966-67 fuel burn log sheet records were obtained for each. An attempt to correlate daily fuel consumption for each building during the sample month of December 1966 by means of the degree day method met with indifferent success. Discrepancies as large as 40% were encountered between the actual daily fuel consumption and the degree day prediction based on monthly total fuel burn. It is not surprising that the greatest errors (underestimates) were associated with relatively warm sunny days, since the base load, which is not sensitive to degree days, would tend to predominate on warm days, and because the "open window thermostat" effect would tend to make the buildings "leakier" during such periods. It was, evident that, to obtain reasonably accurate daily emission predictions for large residential structures, some refinement of the degree day method would be required. To effect this, two studies were initiated.

Empirical Fuel Use Prediction

Daily fuel burn data for the three CHA complexes, the Illinois Institute of Technology heating plant and the University of Chicago heating plant (Data for the latter plant had been procured because of its central location in Hyde Park) were compared with the corresponding degree-day prediction of daily fuel burn. A remarkably good correlation of the errors associated with each plant was observed. That is, the percentile discrepancies between the actual and degree-day predicted fuel consumption correlated within about 10% for each of the five reference plants for the sample period of December 1966. A computer program was therefore developed within which degree day data for 1966-67 was stored and which, using daily fuel consumption data for the five reference plants, yielded, for each day of 1966-67, a degree day correction factor which represented the average over the five plants. By means of this rather crude empirical scheme, the degree day prediction of the daily fuel consumption for any structure in the large residential class could be adjusted by the empirical correction factor derived for the five sample plants. The input to this program for a given building or group of buildings of the large residential class within a given square mile sector would thus be a single, annual fuel consumption figure. This annual datum would be reduced to daily fuel consumption data by the degree day method and then corrected by the empirical correction factor for that day to yield an actual daily fuel burn. The major discrepancy associated with this empirical approach involves the fact that certain large heating plants are equipped with dual fuel capability and therefore occasionally burn natural gas. In order to account for this effect, it is necessary to include within the final emission data processing file, information concerning the availability of interruptible gas during the 1966-67 period. It will probably not prove feasible, within the existing program schedule, to seek out and adjust large dual fuel residential emissions for this effect, however considering the relatively small number of residential steam plants that are equipped with dual fuel capability and the relatively small contribution to the total SO_2 background of any one residential source, it is believed that this approximation can be accepted.

Statistical Heating Load Prediction

A somewhat more sophisticated approach to the prediction of space heating fuel consumption was undertaken in parallel with the empirical fuel use study described above. This involves the use of multivariable regression analysis techniques to derive a general statistical correlation between meteorological variables and fuel consumption for a space heating SO_2 source.

On the basis of information supplied by the Peoples, Gas, Light and Coke Company and the Commonwealth Edison Company, it was concluded that any attempt to regress on meteorological variables independently, i.e. degree-day, hours of sunshine, wind velocity, temperature variation, etc. would fail - primarily because the predominance of the degree day parameter would mask the less significant variables. It was therefore decided that other meteorological variables would be regarded as correction factors for the degree day parameter so that the desired regression equation would have the form

$$F = DD\,[C_o + (C_1 \cdot S) + (C_2 \cdot W) + (C_3 \cdot \Delta T) + ----]$$

where

F = Space heating fuel use

DD = Degree Day parameter

S = Hours of sunshine

W = Daily average wind

T = Daily temperature change

$C_o, C_1, ---C_n$ = Correlation Coefficients

An alternative regression equation which reflects the base load would have the form:

$$F = C_o + C_1 \cdot DD\,[C_2 + (C_3 \cdot S) + (C_4 \cdot W) + (C_5 \cdot \Delta T) + ----]$$

The data employed for this analysis are those associated with the five sample plants for December 1966. The statistical study is now in progress and should be completed by the end of January 1968.

Once an accurate scheme for the prediction of daily fuel use in large residential structures has been developed, an hourly breakdown of the daily fuel data will be obtained by means to be described subsequently.

Small to Medium Residential Fuel Use Patterns

Automatically Stoked Plants

Coal or oil fueled heating plants in small to medium sized apartment buildings (3-55 dwelling units) are generally automatically-stoked, gravity return systems which are allowed to idle (i.e. stoking is limited to 6 minutes per hour) from about 11:00 PM to 5:00 AM daily. During the day, therefore, the fuel burn pattern in such buildings tends to follow the hourly temperature trend (with a time lag appropriate to the building size), but at night a fairly abrupt reduction in SO_2 emission occurs. Emissions are low during the night and then, during the morning heat-up period, a very high rate of emission prevails until the building has been brought up to the thermostatically controlled temperature level again.

The emission schedule for such structures would thus correspond to that of an automatically stoked heating plant modified by an empirical pattern dictated by the procedures of the building superintendent in his efforts to minimize fuel use while complying with city ordinances which dictate the minimum temperatures allowed in residential buildings. This modifying pattern was designated "Janitor Function" and an investigation of the elements that determine it was initiated.

The Janitor Function

Residential emission data for the Hyde Park sector of Chicago was of the greatest immediate concern because that area was selected for the pilot study which would serve as a test of the proposed statistical dispersion modeling technique. Moreover, coal and oil fired heating plants predominate in that sector of the city. Hyde Park was therefore selected as the most logical area in which to investigate the "Janitor Function".

Buildings with Similar Heating Patterns

Except for a few large buildings/complexes such as University of Chicago, the Windemere Hotel or CHA, virtually all of the residences in Hyde Park have automatic-stoker-fired, gravity return heating systems which turn on at 4 or 5 AM and off at 10 or 11 PM (occasionally as late as 12 PM or 1 AM). Thus nearly all Hyde Park heating can be described by the same degree day/janitor function pattern. The remaining buildings are either thermostatically controlled gas heated units or large buildings or building complexes with high pressure steam heating which operates full time.

Patterns of Daily Coal Use

Interviews with Hyde Park Building Superintendents resulted in the development of the following average fuel use tabulation for residences with gravity return, stoker fed systems:

Table 4.1

Temp. (°F)	Degree Day Value based on 65°F	Minutes to Heat Up in AM	Minutes of Stoking Per Hour During Heating Hours
0	65	60*	25
20	45	30-40	15-20
30	35	25-30	15
40	25	20	10
>55	<10	--	6

*About 1-1/4 ton of coal. The stoker is usually an on-off device with a single feed rate setting. Numerical value for a typical six-flat.

The six minute per hour "hold fire" figure applies throughout the year, 24 hrs/day and it supplies hot water in the summer. (This is equivalent to about 1/7 ton of coal per day for a six flat building. These estimates should apply to most buildings, since boilers are sized to match heating requirements.

The data may be rewritten based on 55°F with about 6 minutes substracted from all values. This 6 minute period would then be considered as a constant background. The choice of 55°F is based on the fact that thermostats are generally set to 0 (i.e. no heating) when the outdoor temperature exceeds 55°F. This modification is shown in Table 4.2.

Table 4.2

Temp. °F	D. D. Value Based on 55°F	Minutes To Heat Up -5	Minutes of Stoking Per Hour During Heating Hours -5
0	55	55	20
20	35	25-35	10-15
30	25	20-25	10
40	15	15	5
>55	0	0	0

Both tables are presented graphically in figure 4.7. If this data is used in formulating a degree day/janitor factor function, it seems best to use the Table 4.2 format with the 6 min/hour value as a constant background which should automatically be included in the constant term of a statistical regression equation. Thus one might represent the morning heatup time in minutes by:

$$HU = .9 \times DD_{55} \tag{4.1}$$

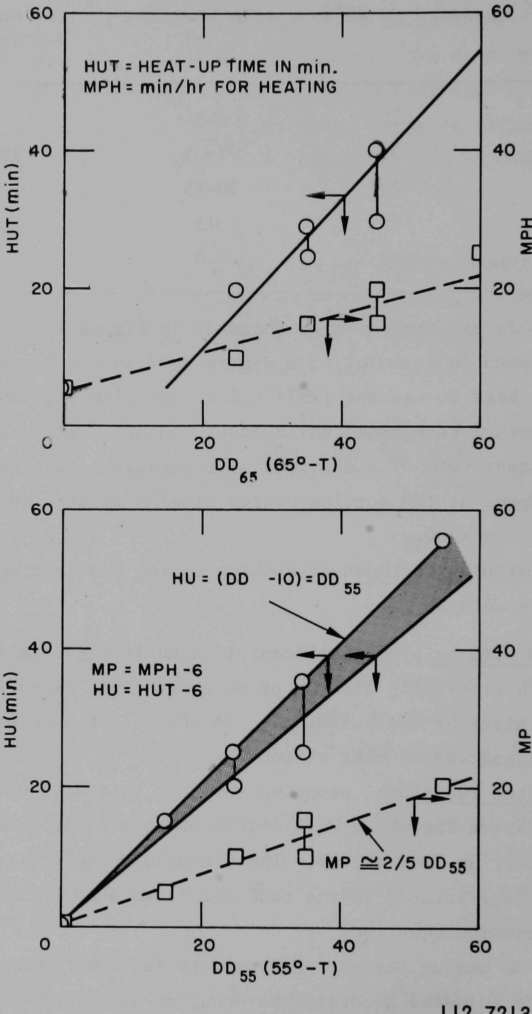
and the minutes per hour of stoking during the heating hours by:

$$MP = .4 \times DD_{55}. \tag{4.2}$$

Wind effects are significant in high leakage six flat buildings with protruding alcoves or porches. This is not so for more uniform airtight CHA buildings. No useful estimate was available on the magnitude of this effect.

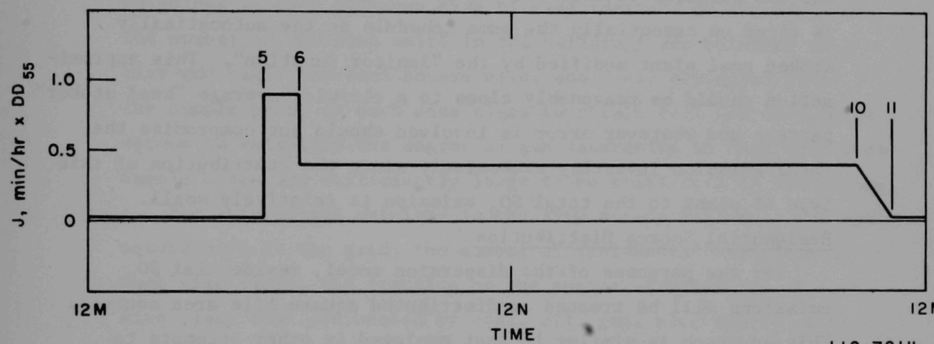
Janitor Function: proposed format. This does not consider the transport lag which will distribute the early morning SO_2 output over an hour or two. The 6 min/hour "hold fire" is assumed incorporated in the constant background term of the fuel use regression equation.

The AM heatup period is assumed to last one hour with the magnitude adjusted according to equation 4.1. Thus the vertical scale is in minutes per hour. Beginning the day at 5 AM seems reasonable since very few buildings begin their warm-up before 5 AM. Similarly, although University owned residences often maintain heating until midnight or 1 AM, most boilers shut down sometime



112-7213

Fig. 4.7 Residential source heat-up correlation



112-7214

Fig. 4.8 Proposed janitor function

between 10 and 11 PM (almost always at 10 PM when the outside temperature exceeds 30°F). Figure 4.8 presents a possible janitor function.

Hand Fired Residential Coal Plants

Approximately 11% of all residential SO_2 emissions are attributable to hand-fired coal burning heating plants. This corresponds to about 1.6% of the total annual SO_2 emissions for the city. To develop a rigorously accurate stoking pattern for small plants of this type is regarded as impractical in view of the predominance of the "human factor" in the pattern and the extensive scope of the surveying effort that would be required to obtain enough data to develop a meaningful correlation. It will therefore be assumed for the purposes of this study that the hand stoked heating plant is fired on essentially the same schedule as the automatically stoked coal plant modified by the "Janitor Function". This approximation should be reasonably close to a citywide average "hand stoker" pattern and whatever error is involved should not compromise the total emission inventory excessively since the contribution of this type of plant to the total SO_2 emission is relatively small.

Residential Source Distribution

For the purposes of the dispersion model, residential SO_2 emissions will be treated as distributed square mile area sources. This approach is similar to that employed in other attempts to develop computerized air pollution dispersion models [1,2] and is justified by the wide distribution of residential sources and the virtually infinitesimal contribution of any given source to the city-wide emission pattern. The selection of square mile unit areas for the model was indicated by virtue of the fact that the comprehensive 1964 annual emission inventory performed by the Chicago DAPC and the current effort to update that inventory are both based on a square mile grid system. Further, one of the major sources of information with regard to the city-wide distribution of fuel burning SO_2 sources - the Rates and Markets Department of the Peoples Gas Light and Coke Company (PGLC) of Chicago - bases its survey procedure on the same square mile grid employed by the DAPC. Moreover, the essentially Cartesian layout of Chicago lends itself to treatment by square miles; city planning is done on this basis; and finally, this unit size is convenient for a system which has dimensions of roughly 12 miles by 25 miles and within which the prime data acquisition network (the TAM system) consists of a series of stations separated by a distance of 6-7 miles.

People's Gas Rates and Markets Survey

One of the major advantages of the square mile grid system was its compatibility with the PGLC Rates and Markets surveys of fuel burning sources. The most recent set of these sampling surveys was conducted in 1960 and 1962. PGLC maintains current Sanborn maps which indicate, within each block in the city, the size and type of each building. By means of these maps, groups of sample buildings in each of seven size classes (defined on the basis of the number of dwelling units in the building) are selected on a city-wide basis for each square mile, and field personnel visit the sample group in each size class to obtain fuel use data which serves to establish the degree of gas saturation in that unit area. Sample sizes are sufficiently large to be statistically satisfying.

The information obtained in the 1960 survey includes, for each square mile in the grid; the number of residential buildings in each size class, the fraction of the number of buildings of each size class that are heated by coal, oil, gas, electricity, etc. and the type of heating unit used (central heating plant, individual apartment heaters, etc.). The 1962 survey obtained the same data with regard to the square mile distribution of buildings of each size class, but established the use of different types of fuel by each size class of building on a city-wide rather than a square mile basis. PGLC is currently in the process of developing a current version of this survey (1966-67), but the results are not likely to be available until mid-1968. Because of the rapid rate of demolition and building in Chicago, current information with regard to residential fuel burning patterns is desirable and, will, it seems, be available from two independent sources - the DAPC and PGLC - in mid-1968, but it is evident that the initial version of the residential emission inventory will have to be based on the 1962 PGLC survey, since the program schedule cannot admit the required delay involved in obtaining current data. When the current data becomes available it will be incorporated in the master emission data file and used as a part of the refinement phase of the dispersion modeling effort.

Residential Fuel Consumption

With the distribution of space heating sources, of fuel types and of heating plant types established as indicated above, it is necessary to determine the actual quantities of each fuel required to heat buildings of each size class. The technique employed by the DAPC for their 1964 annual inventory appears to be appropriate for this purpose. PGLC was able to supply typical annual gas heating requirements for each of the seven size classes of buildings surveyed by their Rates and Markets department. These quantities may be converted into therms of heat energy which may, in turn, be reduced to equivalent amounts of stoker or hand fired coal or to quantities of one of the several grades of fuel oil, by means of the known heating value of the fuel and an efficiency factor associated primarily with the size of the heating plant involved.

Table 4.3 (developed by the DAPC) shows these fuel equivalents and the assumed plant efficiencies, and table 4.4 indicates the residential coal burning profile of the city. Data acquired from five sample plants (CHA, the Illinois Institute of Technology and the University of Chicago) provide confirmation of the technique for large plants and surveys of smaller plants provide equivalent validation for the lesser residential sources.

Hourly Space Heating Fuel Use Correlation

As indicated above, various satisfactory approximation techniques are available or can be developed to estimate annual, monthly or daily fuel use by space heating plants, but, in the last analysis, an acceptable technique for obtaining hourly emission data is required after the coarser breakdowns are effected. To achieve this, three alternative sources of real-world heating data for 1966-67 will be exploited. These are the hourly records of the University of Chicago steam plant, the hourly gas sendout records of PGLC and the results of an experimental fuel consumption study for small apartments.

Table 4.3

QUANTITIES OF GAS, OIL AND COAL USED YEARLY

PER DWELLING UNIT BY DIFFERENT SIZED RESIDENTIAL BUILDINGS

Number Of Apartments/Building	Gas (Cubic Feet)	Oil Gallons	Coal (Tons)
1	140,000 (.80)	1,068 (.75)	6.48 (.64)
2&3	126,733 (.80)	965 (.75)	5.86 (.64)
4-7	109,840 (.80)	837 (.75)	4.78 (.68)
8-19	95,000 (.80)	726 (.75)	4.14 (.68)
20-59	80,000 (.80)	610 (.75)	3.16 (.75)
60^+	72,000 (.80)	549 (.75)	2.84 (.75)

Figures in parenthesis indicate burning efficiencies of the fuel burning equipment.

Table 4.4

PROFILE FOR COAL BURNING

Number Of Apartments/Building	Percent Stoker Fired	Percent Hand Fired
1	28	72
2	70	30
3	75	25
4-5	80	20
6-7	85	15
8-19	90	10
20^+	95	5

University of Chicago Steam Plant

The University of Chicago operates a large and well instrumented four boiler, central steam plant which provides space heating for a major complex of academic buildings covering an area of about six square blocks in the Hyde Park sector of Chicago. This plant accounts for about 0.3% of the total annual SO_2 emissions and is therefore one of the largest space heating facilities in the city. Each of the structures for which it supplies steam is roughly comparable to a medium-sized apartment building.

Because of the proximity of this coal fired plant to the Hyde Park TAM station, it was decided that it should receive individual treatment as an SO_2 source. The excellent set of hourly steam flow records, daily fuel consumption and sulfur content analysis records maintained by the University make it possible to derive extremely accurate hourly fuel consumption and SO_2 emission data. The reduction and computer processing of raw data from this plant for 1966-67 were essentially complete at the end of the first quarter of the program.

It was observed, as noted previously, that, on a daily fuel use basis, the fuel consumption pattern for the University corresponded well with that of the three sample CHA complexes - a fact which tends to verify the essential equivalence, from a space heating standpoint, of the University buildings and the CHA apartments. On this basis, it was concluded that the University of Chicago data could serve a dual purpose by providing a normalizing reference point for all high pressure steam heating plants in the inventory for each hour of each day of 1966-67. The processing of high pressure steam plant data on this basis is scheduled to begin in the latter part of January.

Gas Sendout Records

Hourly records of the total gas sendout for Chicago are maintained by PGLC. This data does, of course, include the effects of the combined space heating and processing load for all residences, commercial buildings and industrial plants in the city. To factor the base and processing load out of this data, records for zero degree (∿65°F) days, when neither heating nor cooling equipment would be expected to be in operation, can be correlated with heating days. This method, effectively that devised by Turner (ESSA, Cincinnati), yields a city-wide real-world hourly normalizing factor for all thermostatically controlled, twenty-four hour operational heating plants. Its major deficiencies are associated with the fact that it fails to take account of the "Janitor Function" effect for older, small-to-medium sized structures and of the open window effect observed for large, low-income, coal heated structures such as the CHA buildings. It avoids the major weakness of any sort of sampling technique such as those described previously, since it represents a true, real-time, city-wide heating load correlating factor.

To check the validity of the University of Chicago correlation, gas sendout records for December of 1966 have been obtained.

Building Instrumentation

In order to establish an hourly reference correlation for small apartment buildings of the kind that predominate in Hyde Park and to validate the fuel consumption assumed for low pressure steam plants of this class, the prospects of instrumenting several sample structures were investigated. It was found that the fuel oil supplier was prepared to instrument selected, oil-fueled apartment heating plants as a public service. A selection of sample buildings in the Hyde Park area is now being made in conjunction with PGLC and the DAPC. These structures will be instrumented and representative hourly data for 1-2 heating months will be obtained.

The possibility of devising simple and inexpensive instrumentation to obtain comparable data for low pressure coal-fired plants in selected buildings is now under study. The sample buildings for both types of fuel are those recommended by PGLC and will be chosen to correspond to the same classes employed for their rates and markets surveys.

4.4.4 Commercial Sources

Heating plants associated with large commercial structures account for approximately 8.3% of the total annual SO_2 emission in the city. Following the format established by the DAPC, the term "commercial building" is intended to include such diverse structures as office buildings, large stores, hospitals, convents, warehouses, etc. The coal or oil fired heating plants used in these structures are generally of the high pressure, automatically stoked variety and can be expected to follow the same general hourly fuel use pattern as that established for large residential buildings.

The distribution of commercial buildings on a square mile basis was established by the DAPC for their 1964 annual inventory by means of data from the PGLC surveys described previously. The distributions of fuel use and heating plant types were also determined, on a city-wide basis, during this inventory operation.

Fuel use factors for commercial buildings of five size classes were developed for the DAPC inventory. This information can therefore be combined with source distribution, fuel type and heating plant data and the hourly fuel use correlating factors generated by means of the University of Chicago heating plant study to establish hourly SO_2 emission data for commercial structures.

Partial validation of this technique will be obtained via a sample study of fuel use records of the Union Station. This heating plant accounts for 0.72% of the total annual SO_2 emissions for the city and is therefore a major source in itself. The Union Station data will be supplemented by the fuel use records of the Cook County Hospital which operates a large, oil-fired heating plant which is responsible for 0.07% of the annual total emissions.

The inherent weakness associated with excessive reliance upon a few samples in order to validate a proposed general fuel use pattern for a large number of diverse structures is evident, however the magnitude of the task of obtaining a statistically satisfying sampling dictates this approach.

The acceptance of what is essentially 1960-62 commercial source distribution data for the purposes of the hourly inventory represents less of a compromise of accuracy than is the case for residential buildings, because the rate of change of population in this class of structures is inherently slower than for residential buildings.

CHICAGO AIR POLLUTION DISPERSION MODEL

5.0 Applied Programming

F. Clark
A. Kennedy

5.0 Applied Programming

The programming and data processing effort to date has evolved in two areas as follows:

1) data processing, file generation, and retrieval;

2) programs associated with the modeling effort.

As can be expected during the initial phases of the project, much of the programming effort has been concentrated in area 1); however progress has also been made with regard to the modeling effort, as described subsequently in this report.

5.1 Data Processing, File Generation, and Retrieval

Thus far, the programming effort has been primarily concerned with the three task areas outlined below. Most of the work accomplished to date has centered around the Telemetered Air Monitoring (TAM) network data, but in the immediate future more effort will be concentrated on the meteorological aspects of the project.

5.1.1 TAM Network

The data set furnished by the DAPC to date is restricted to the period January 1, 1966 to August 1, 1967.

Hourly SO_2 Averages

In order to get the fifteen minute air quality and wind data into a form that could be used effectively, it was necessary to convert it into hourly averages. The averaging process involved an initial sorting of the data tapes to yield a data set in time sequence, since, for a given time, the readout data for the eight TAM stations were originally recorded in station sequence. The required sorting operation was accomplished by means of a standard IBM sort routine on the IBM 360/75 computer. The process required approximately 20 minutes of computer time to sort about 350,000 records. After producing a sorted magnetic tape, it was then necessary to generate hourly averages from the fifteen minute data. This was accomplished on the CDC 3600 computer by means of a FORTRAN program.

The averaging process involved the consideration of five readings (in the general case) for a given hour. Specifically, in order to determine the average SO_2, wind direction, and wind speed for hour n, the sequence of readings taken at n-30 minutes, n-15 minutes, n, n+15 minutes, and n+30 were averaged. This procedure is more consistent with the methods used to develop hourly records of meteorological data than a straightforward averaging of readings taken during a given hour would be; i.e. consideration of the readings n, n+15 minutes, n+30 minutes, and n+45 minutes.

The average SO_2 reading was derived by a simple averaging process for (at most) five consecutive readings. The wind direction and wind speed averages, however, were calculated as follows:

Given the wind direction readings θ_i, i=1,2,3,4,5 and the wind speed readings S_i, i=1,2,3,4,5

$$x_i = S_i \cos \theta_i \quad , \quad i = 1,2,3,4,5$$

$$y_i = S_i \sin \theta_i \quad , \quad i = 1,2,3,4,5$$

$$X = x_1 + x_2 + x_3 + x_4 + x_5$$

$$Y = y_1 + y_2 + y_3 + y_4 + y_5$$

Having thus found the legs of a resultant right triangle, the resultant speed and direction are determined from:

$$\theta = \tan^{-1} \frac{Y}{X}$$

and

$$S = (Y^2 + X^2)^{1/2}/5$$

It is important to keep track of the quadrant location of θ. This is accomplished automatically due to the characteristics of the arctangent routine used. It is equally important to take account of the fact that there may be data items missing for any given hourly sequence. Therefore, only in the general case are five consecutive readings considered.

Data File Structure

The data file resulting from the averaging process described above constitutes the first attempt at determining a reasonable format for variable usage of hourly data. The FORTRAN program written to produce the hourly averages established the format as follows:

Item	Character Positions	
Month	1-2	
Day	3-4	
Year	5-6	
Julian Date	7-9	
Hour	10-11	
Station	12-13	Repeated 8 times. Once for each station.
SO_2	14-16	
Wind Direction	17-19	
Wind Speed	20-22	
.	.	
.	.	
.	.	
.	.	
.	.	

The total number of characters required for a particular hourly data item is, therefore, 99. On tape, the data are blocked 40 hours per block, meaning that a physical record on tape is 40x99 = 3960 characters in length.

Retrieval Programs

1) A scanning program was written in CDC 3600 COBOL to allow the user of the processed TAM tape to specify a given range of SO_2 concentration for observation. Specifically, given a range (e.g. 0.1-0.2 PPM) of SO_2 concentration, a report is printed for a specified range of days giving the pollution concentrations within that SO_2 range. This report represents a frequency indication for the selected pollution level. Only readings in the chosen range are printed - blanks appear elsewhere.

2) A retrieval program was written in CDC 3600 FORTRAN to search the hourly average TAM tape for a particular hourly average. The process involves an efficient reading routine to skip those blocks of data not under consideration in order to arrive at the particular point in question.

3) A program is currently being written to produce daylight and night-time averages of SO_2 concentration for the period

covered by the TAM data. In particular, an average is requested for the SO_2 concentration as observed by each TAM station) during the periods 6:00 AM to 6:00 PM and 6:00 PM to 6:00 AM for each day from January 1, 1966 through July 31, 1967. The number of readings employed in the averaging process is of special interest for this data survey.

5.1.2 Emission Inventory

Processing Programs

It is anticipated that many processing programs will be written to examine specific emission patterns. For this reason, a library of such programs is being developed. Among the first emission data processing programs in this library is COALPILE. This is a CDC 3600 FORTRAN program designed to yield hourly SO_2 emissions and exit temperatures from each of two stacks at the University of Chicago power plant. The processing procedure is essentially as indicated in the flow diagram (shown in fig. 5.1).

Data File Structure

It is expected that each of the programs in the Emission Inventory library will contribute to the overall file structure. As yet, however, the format for the data file has not been defined. This task will be performed as the Emission Inventory Library approaches completion.

Retrieval and Report Programs

It is further expected that a significant portion of the Emission Inventory programming effort will involve the creation of retrieval and storage programs. These will be developed in conjunction with the data file described above.

5.1.3 Meteorological Data

Programming activities associated with meteorology studies will be broken down into the following three categories:

1) Processing Programs;
2) Data File Structure; and
3) Retrieval and Report Programs.

A data set is currently being created from the meteorological data now at hand. This includes the Weather Bureau record tapes for Glenview, O'Hare and Midway Airports as well as the documentary

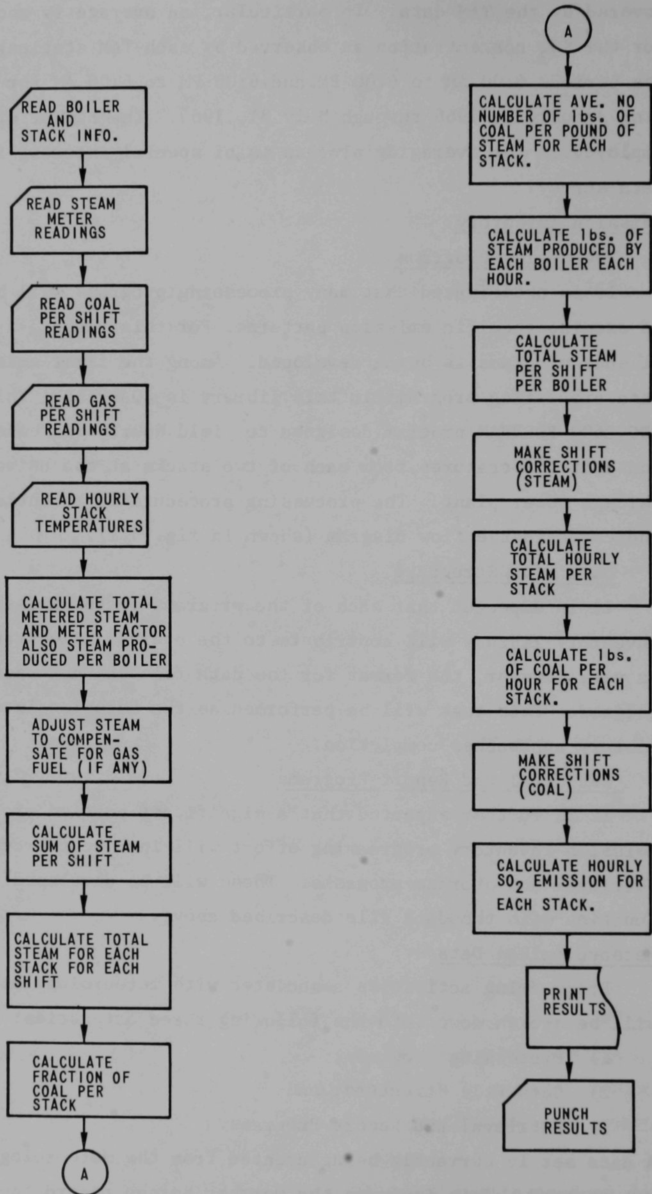


Fig. 5.1 Program coalpile flow chart

records from Meigs Airport and other data as described in section 3.0 of this report. A general format for this data base, including the TAM data, is shown in Fig. 5.2.

5.2 Modeling Effort

As mentioned above, the programming effort has thus far concentrated on the "data processing" aspects of the project. Two significant accomplishments in direct support of the modeling effort are:

1) The St. Louis dispersion model has successfully executed a sample problem on the CDC 3600 computer.
2) A multiple linear regression code has been programmed and successfuly tested on the IBM 360 computer.

It is anticipated that this regression code will be used extensively for initial data analysis as well as for the dispersion modeling studies.

DATA BASE FORMAT (YEARLY)

DATA RECORDS ORDERED BY DATE/HOUR

	PARAMETER				
SOURCE	TEMP.	WIND DIR.	WIND VEL.	SO_2	.....
TAM 1					
⋮					
TAM 8					
O'HARE					
⋮					

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Fig. 5.2 Data base format (yearly)

CHICAGO AIR POLLUTION DISPERSION MODEL

6.0 Air Pollution Economics and Abatement Strategy

A. Kennedy

E. Croke

6.0 Air Pollution Economics and Abatement Strategy

6.1 Optimal Abatement Model

Given the predictive capacity of an effective dispersion model and the availability of certain types of control of major pollution sources, along with the associated costs of such control, it is feasible to formulate a simplified linear programming model of a least cost program for avoiding pollution "incidents" (pollution concentrations exceeding a specified level) associated with dispersion which may occur when a "mean" wind direction and velocity prevail.

6.1.1 The Prediction Model

Using the format of the general, statistical technique discussed in section 2.0 of this report, it is possible to infer that the SO_2 dispersion prediction will be formulated as described in the following discussion for situations characterized by an average wind direction and velocity.

Let $P_i(t)$ be the pollution concentration measured at receptor i at time t and $S_j(t)$ be the SO_2 emitted from source j, one seeks to determine, for each meteorological regime, coefficients a_{ij} and b_i such that

$$P_i(t) = \sum_{j=1}^{J_i} a_{ij} S_j [t - \tau_{ij}] + b_i \qquad (6.1)$$

$$i = 1,2,\ldots,I$$

where

J_i is the number of sources assumed to be affecting receptor i,
a_{ij} is the "level" at which source j is affecting receptor i,
b_i is the constant background pollution level at receptor i,
τ_{ij} is a time delay depending on the meteorological conditions and the distance from the point j to the receptor i,
I is the number of receptors.

With hourly emission data available for the years 1966-1967 and appropriate meteorological "regimes" identified for this period, the following set of simultaneous linear equations is obtained for each regime:

$$P_i(t_n) = \sum_{j=1}^{J_i} a_{ij} S_j (t_n - \tau_{ij}) + b_i \qquad (6.2)$$

$$n = 1,2,\ldots,N$$

where

N is the number of hours that the particular regime was in effect during the two year period.

A least squares solution of equations (6.2) yields the a_{ij} and b_i. Thus, short range weather forecasts can be used to select a particular weather regime and, coupled with current emission patterns for each source, equation (6.1) can be used to predict SO_2 concentrations at each receptor i.

Equation (6.1) therefore represents a linear prediction model in which it is assumed that:

1) the SO_2 concentration observed at receptor i from source j is proportional to the SO_2 being emitted at point j;
2) the sources contributing to the pollution at receptor i add to give the total effect at the receptor.

It should be noted that these linearity assumptions are reasonable, since equations governing the transport of pollution involve a linear transport term in the downwind direction and a linear diffusion operator for periods within which a constant mean wind prevails.

6.1.2 Methods of Pollution Control

Sulfur dioxide emissions resulting from the burning of high sulfur content coal are considered to be a major source of air pollution. Unfortunately, during the peak heating seasons, high sulfur content coal or oil, the cheapest fuels available, are burned by major industrial, commercial, and large residential boilers. Some possible forms of emission control are listed below:

Limitations on the Sulfur Content of Coal or Oil

Limiting the percentage of sulfur in coal or oil has been suggested as one form of control. However, an economical means of physically reducing the sulfur content of large quantities of these fuels has not yet been developed. For the present analysis this form of control will not be treated.

Dual Fuel Installations

Fortunately for control purposes, many large coal burning installations are "convertible"; that is, they are capable of converting to a clean fuel (usually natural gas) on short notice if it is economical to do so. This is, in fact, the case during the off-peak heating season, when gas is readily available at reduced rates. Likewise, during winter periods, if gas can be made available (even at increased rates), large SO_2 emitters with conversion capability can switch to gas during pollution incidents. Naturally, the amount of gas to be made available and its rate are subject to negotiation between each installation and the gas company. Thus far, this form of control seems to be the most acceptable.

Electrical Power Load Shifting

As might be expected, electrical power plants are a major source of SO_2 emissions, contributing more than 65% of the total emissions in the city of Chicago each year. Any control program will obviously include these plants. Fortunately, many power plant boilers are convertible. In addition, urban power plants are capable of shifting a certain amount of their electrical load to extra-urban plants in off peak hours, thus reducing the amount of SO_2 produced within the metropolitan area. However, this must be considered as a secondary form of control since the expected percentage of the load that can be shifted is not particularly high for any given time. The Chicago power plant system is capable of shifting about 11% of its load 99% of the time, 22% load about 50% of the time and 50% during minimum power demand periods.

On-Off Control

Those industrial, commercial, and large residential installations for which coal is the only energy source must be controlled in an on-off fashion. That is, either the installation must be allowed to continue its coal burning program, or it must be curtailed to some subsistance level. It is reasonable to expect that costs for such control would be difficult to estimate and undoubtedly high.

6.1.3 Approximations and Assumptions

For the purposes of this analysis, certain assumptions will be made regarding the costs and control variables associated with a linear programming optimal abatement model so that a simplified formulation will result. The approximations discussed here tend to involve a certain degree of idealization; however, it should be emphasized that useful experience can be gained by considering the model in its simplified form.

Cost Functions

It will be assumed in the present optimal model formulation that the cost per percent reduction in SO_2 being emitted is constant for each plant. A more rigorous generalization to "cost functions" would include the following effects:

1) the cost of reducing SO_2 emitted may vary with time (e.g. gas may be cheaper during early morning than late afternoon);
2) each plant j may have "cost levels"; that is, the reduction per percent reduction in SO_2 may cost C_{1j} dollars up to a certain percent L_{1j}, C_{2j} dollars up to a percent L_{2j}, etc.

For the simplified case, the formulation is not changed except that the costs are considered to be fixed instead of being functions of time (i.e., $C_j(n)$). The second approximation involves the neglect of a set of control variables for each plant j (one for each cost level) and therefore assumes a single "cost level" for each plant.

It will also be assumed that the costs per percent reduction in SO_2 are linear.

Reduction Functions

For simplicity, the present approximate model formulation will assume that the reduction functions $X_j(t)$:

1) may assume all values between $L_j(t) \geq 0$ and 100;
2) are continuous functions of time (i.e., control changes can be made at least on an hourly basis.

In a more rigorous model, "control levels" $L_{k,j}(t)$, $k=1,2,\ldots,K_j$, may be introduced (for reasons of cost or because of physical constraints) such that:

$$100 = L_{o,j}(t) \geq L_{1,j}(t) \geq \ldots \geq L_{K_j,j}(t) \geq 0 \qquad (6.3)$$

In this case, it is necessary to introduce the "set" of control variables, $X_{k,j}(t)$, such that

$$L_{k-1,j}(t) \geq X_{k,j}(t) \geq L_{k,j}(t) \qquad (6.4)$$

Thus, the dimensionality of the problem is increased.

It may also be required that the "control levels" be equalities, i.e.

$$X_{k,j}(t) = L_{k,j}(t) \qquad (6.5)$$

Note that requiring integral control level equalities leads to a "mixed integer" programming problem. This complication is neglected for the present analysis.

There may exist "time lag" or "set up" constraints of more than one hour on the control variables, or "hourly tie-in" constraints such that, once a certain level of control is achieved, it cannot be varied for periods exceeding one hour. Such constraints may lead to a "stage by stage" analysis (each hour being a stage) where a dynamic programming[5,6] formulation may be applicable for optimizing the model over the length of the pollution incident. This refinement is neglected for the present approximate analysis.

Within the limits of the approximations discussed above, the optimization model described in the following section was formulated.

6.1.4 Formulation of the Linear Programming Model

A plant is considered to be controllable if there is an attainable percentage reduction function X(t) and a limit function L(t) associated with the plant such that:

$$100 \geq X(t) \geq L(t) \geq 0$$

and

$$\overline{S}\ (t) = \frac{X(t)\ S(t)}{100}$$

yields a reduced emission from the plant at time t. Thus, a plant is not controllable if L(t) = 100. For the present, assume that X(t) can have all values between L(t) and 100, and that X is a continuous function of t, (i.e., control is instantaneous). It will be noted that X(t) exists if the plant has available one or more of the forms of control described previously.

If J_i is the number of plants affecting receptor i, let J_i^c be the number of controllable plants and J_i^N the number of non-controllable plants, and order them $j=1,2,\ldots,J_i^c + 1,\ldots,J_i$. That is, the first J_i^c are controllable and the remainder are not. Letting $\overline{P}_i(X_1,\ldots,X_{J_i^c},t)$ be that part of the reading at receptor i due to controllable plants then

$$\overline{P}_i(X_1,\ldots,X_{J_i^c},t) = \sum_{j=1}^{J_i^c} \overline{a}_{ij}\ (t-\tau_{ij})\ \frac{X_j}{100}\ (t-\tau_{ij}) \tag{6.6}$$

where

$$\overline{a}_{ij}(t-\tau_{ij}) = a_{ij}\ S_j\ (t-\tau_{ij})$$

If P ppm is a maximum acceptable pollution level, it is desirable to establish:

$$\overline{P}_i(X_1,\ldots,X_{J_i^c},t) \leq P_i^{max}(t) \text{ for } i=1,2,\ldots,I$$

where

$$P_i^{max}(t) = P - \sum_{j=J_i^c+1}^{J_i} \overline{a}_{ij}\ (t-\tau_{ij}) + b_i \tag{6.7}$$

Note that for a feasible solution to exist, it is necessary that

$$\overline{P}_i\ (L_1,\ldots,L_{J_i^c},t) \leq P_i^{max}\ (t) \tag{6.8}$$

If it is further assumed that a penalty cost of c_j dollars per percent reduction in the SO_2 emission at plant j, and also that the pollution incident lasts for N hours, the following linear programming model can be formulated for each hour n.

$$\min Z(n) = \sum_{j=1}^{J} c_j \; (1-X_j(n)) \tag{6.9}$$

subject to the constraints

$$100 \geq X_j(n) \geq L_j(n) \geq 0 \qquad j=1,2,\ldots,J$$

and

$$\sum_{j=1}^{J_i^c} \bar{a}_{ij} \frac{X_j(n-\tau_{ij})}{100} \leq P_i^{max} (n)$$

where

$i=1,2,\ldots,I$, the number of receptors,

$j=1,2,\ldots,J$, the number of significant sources.

Thus, solving this problem for each $n=1,2,\ldots,N$, an "emission reduction program", $X_j(n)$, is obtained for each plant j for the duration of the pollution incident.

The objective function can be rewritten

$$\max Z(n) = \sum_{j=1}^{J} c_j \; X_j \; (n) \tag{6.10}$$

Since $\min (-Z) = \max Z$

and $\sum_{j=1}^{J} c_j$ = constant

This formulation is referred to as the primal problem, and standard techniques are available for solving this system of equations.

It will be noted that, for this formulation, the restriction that X(t) is a continuous function of t may be relaxed to that of assuming that control is available on an hourly basis.

6.1.5 Formulation of the Dual

Information may be obtained which is useful for certain purposes by considering the "dual" to the problem formulated in the previous section[7]. The variables in the dual problem are interpreted as the change in the objective function Z due to a change in the P_i^{max}. For example, if it is considered reasonable to impose control on one or more of the noncontrollable plants which affect the reading at receptor i, it may be possible to increase P_i^{max}. The dual variable associated with the i^{th} constraint, w_i, then gives an indication of the total cost decrease* as a result of this added control (assuming the dual solution does not change with a change in P_i^{max}. Thus, w_i may be considered as the value of a unit reduction in reduction in P_i^{max}. The dual to (6.9) and (6.10) is formulated as follows[7]:

$$\min Z^*(n) = \sum_{l=1}^{I} P_i^{max}(n)\, w_i \quad +$$

$$\sum_{j=1}^{J} 100\, w_{I+j} + \sum_{j-1}^{J} L_j(n)\, w_{I+J+j} \tag{6.11}$$

Subject to the constraints

$$\sum_{i=1}^{I} \frac{\bar{a}_{ji}}{100} w_i + \sum_{i=1}^{J} w_{I+i} + \sum_{i=1}^{J} w_{I+J+i} \geq c_j$$

$$j=1,2,\ldots,J$$

where the dual variables satisfy

$$w_i \geq 0 \qquad i=1,2,\ldots,I,I+1,\ldots,I+J$$

$$w_i \geq 0 \qquad i=I+J+1,\ldots,I+2J$$

6.2 Optimal Abatement Test Case

The approximate, optimal SO_2 abatement model described in 6.1 represents no more than a preliminary analysis of the problem of developing an effective abatement strategy. Refinements of the proposed technique are obviously required, and the methodology must be validated with a real-world test case before it can be applied to the Chicago urban system. The following discussion

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* w_1 gives an indication of the increase in (6.10), but the true objective function is (6.9).

suggests a test case which could serve as a useful vehicle for conducting shakedown trials of the optimal abatement model and/or other types of economic abatement strategy. It should be noted that the feasibility of using the test case proposed in the following discussion has not yet been fully established.

6.2.1 Power Plant SO_2 Abatement Economics

A potential test case has been identified which should, if analyzed, serve to lay some of the groundwork for the second phase of the program, as well as yield results of practical value during the first phase. This is based on the fortunate circumstance that a major fraction (about 65%) of the SO_2 released in the Chicago area is produced by six Commonwealth Edison (CECO) power plants (see Appendix I) and that no other single source in the city approaches the magnitude of the emissions from any one of these plants. Several of these utility plants have dual fuel capability and within limits, are capable of shifting power loads from one plant to another. A gas utilization contract appropriate for use in meeting an air pollution emergency during the heating season (when the power plants normally burn coal) has been negotiated between CECO and the gas supplier, and CECO maintains excellent records of its coal and gas consumption (in contrast to most of the secondary SO_2 producers). To an extent, therefore, CECO represents a microcosm of the total abatement problem.

In view of these circumstances, it is both feasible and worthwhile to devise an air pollution abatement gaming strategy based on the control of emissions from the six Commonwealth Edison power plants. It is therefore proposed that the air pollution economic study for the first phase of the ANL program consist of the development of such a strategy and an evaluation of the cost of implementing it. This study would be completed at the end of the first phase of the program and the results could be offered as an integral package containing a methodology of developing an economical abatement strategy, the strategy itself as it applied to Chicago and an estimate of the economic implications of the strategy.

If the development of such a gaming strategy is undertaken, it would be with the understanding that it in no wise represents an attempt to impose arbitrary regulation by the city or any federal agency upon normal CECO operations or operating procedures. Such a study would be conducted solely in the context of the development of techniques which could be employed to analyze the total Chicago air pollution abatement problem and to devise city-wide abatement strategies.

6.2.2 Key Components of the Power Plant Study

The components of the power plant SO_2 abatement economics study would be as follows:

1) A Computerized Climatological Simulation

A relatively simple climatoligical computer simulation which would reflect the incidence of stagnations in the Chicago area can be constructed by combining the data presented in the Murray and Trettel study "The Climatology of Air Pollution in Northeastern Illinois" - (based upon analysis of meteorological data from 1936 to 1964) with a random number generating subroutine which is now available at ANL. This simulation code can be employed to "generate" typical Chicago air pollution years on a computer. Although it could not be expected to supply details regarding the meteorological fine structure of any given pollution incident that it might predict, this simulation would yield gross data such as air temperature, wind direction, velocity range and persistence during stagnations of different durations, monthly and season incidence of stagnations and gross wind data during nocturnal inversions, etc.

2) Power Plant Emission Data

As noted previously, CECO maintains excellent fuel consumption records. The task of converting these records into SO_2 emission data for use with the simple dispersion model is a fairly large one, however it has been undertaken for the benefit of the main dispersion model, and the data - once available - is amenable to computer storage and handling. The required data reduction is now being performed, hence the power plant emission information necessary for an economic study will be available without expenditure of any additional effort.

3) Fuel Switching and Power Load Shifting Data

The costs associated with switching the CECO plants to clean fuel are well established, and the resulting gas contract provides a firm set of constraints within which an abatement strategy must function.

The flexibility with which CECO can shift power loads among its plants and the efficiency of operation of each plant also represent fairly well defined constraints on abatement strategy. This kind of information can be supplied in quantitative form and the standard techniques normally employed by CECO and the gas supplier to forecast power and gas demands can be used to evaluate the feasibility of a given abatement strategy.

4) Development of Optimum Strategies

Ideally, the SO_2 emission data, the simplified dispersion model and the climatological simulation would be used to generate approximate data regarding the magnitude and frequency of pollution incidents in Chicago, and the significance of the contribution of each of the CECO plants to local high SO_2 concentrations. To develop a truly optimum emission control strategy (assuming that SO_2 concentration is proportional to source strength and abatement cost is pooportional to gas vs. coal differential cost) linear programming techniques would be employed as described in 6.1. A standard linear programming code such as MPS could be used, incorporating the various costs and constraints associated with abatement to seek out one or more optimum abatement strategies based on minimization of cost or minimal air quality standards. [Figure 6.1 summarizes the proposed economics and optimal abatement study].

It may develop that there will not be sufficient time available to implement a computerized (linear program) abatement optimization during the first phase of the study. If this were to prove the case, meaningful conclusions could still be drawn from the use of the pollution incident simulation computer code combined with a "manual" analysis of the computer output. That is, the climatological simulator and simplified dispersion model would be developed and used without the added refinement of using computer techniques to seek optimal strategies.

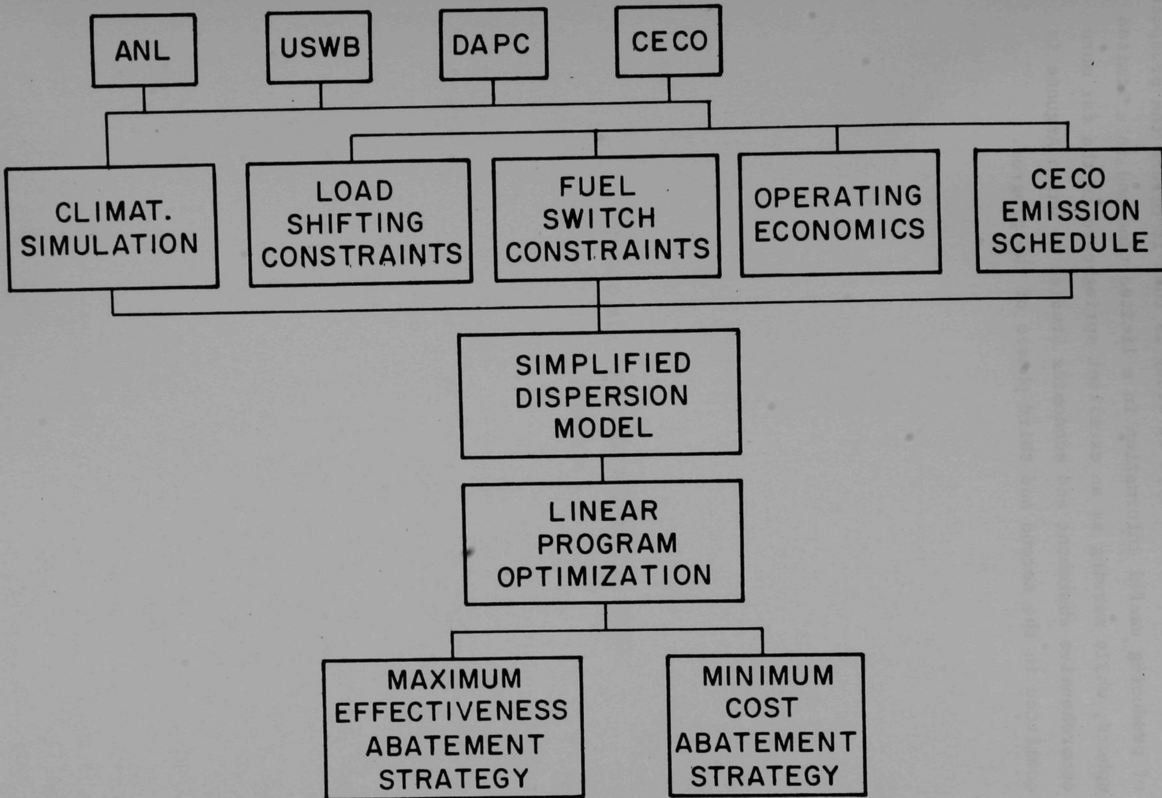

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Fig. 6.1 Abatement strategy and economic study-phase

From the standpoint of the Argonne air pollution program, the major advantage of this type of study is that it offers the prospect of producing useful information in a limited time and in a limited sphere, while serving as an excellent springboard to the far more comprehensive abatement and economics studies to which Argonne is committed in the second and third phases of the program.

CHICAGO AIR POLLUTION DISPERSION MODEL

Appendix I

Appendix I

PERCENTAGE OF SULFUR DIOXIDE
FOR EACH SOURCE IN CHICAGO

UTILITIES	SO_2 tons per year	SO_2 sub-percent	SO_2 grand-percent
1. Crawford	107,954	28.90	18.97
2. Ridgeland	100,540	27.00	17.67
3. Fisk	73,438	19.67	12.90
4. State Line	70,606	18.92	12.42
5. Northwest	10,566	2.83	1.86
6. Calumet	10,016	2.68	1.76
Sub-Total	373,120	100.00	
Grand Percent.			.65.58

COMMERCIAL			
1. Union Station	4,140	8,770	0.7270
2. University of Chicago	1,900	4,020	0.3340
3. Cook County Hospital	387	0.826	0.0680
4. Merchandise Mart	210	0.445	0.0369
5. Tribune Square	160	0.339	0.0281
6. Others	40,419	85.600	7.0960
Sub-Total	47,216	100.000	
Grand Percent.			8.2900

RESIDENTIAL	SO_2 tons per year	SO_2 sub-percent	SO_2 grand-percent
1. Chicago Housing Authority			
a. 48th St. & State Street	558	.6830	.0972
b. 1313 W. Arthington	460	.5540	.0808
c. 418 W. Oak St.	424	.5120	.0745
d. 2437 E. 106th St.	255	.3070	.0448
e. 3640 S. State St.	253	.3050	.0444
f. 24th St. & Federal St.	243	.2930	.0427
g. 37th St. & Wentworth Ave	235	.2830	.0413
h. 2000 W. Diversey Parkway	144	.1735	.0253
i. 2500 W. Harrison	108	.1300	.0189
j. 940 E. 132nd St.	83	.1000	.0146
k. 1834 W. Washington Blvd.	75	.0904	.0132
2. Old Town Garden Apartments	56	.0675	.0098
3. Brockton Tower Apartments	18	.0224	.0032
4. Others	80,115	96.4792	14.0803
Sub-Total	83,027	100,0000	
Grand-Percent.			14.6300

INDUSTRIAL	SO_2 tons per year	SO_2 sub-percent	SO_2 grand percent
1. Marblehead Lime Co.	4,755	7.265	.8350
2. Campbell's Soup Co.	4,416	6.750	.7750
3. Proctor & Gamble Mfg. Co.	3,794	5.800	.6670
4. The Sherwin-Williams Co.	3,297	5.040	.5960
5. Acme Steel Co.	2,920	4.460	.5140
6. International Harvester Co.	2.760	4.220	.4670
7. Container Corp. of America	2,350	3.594	.4130
8. United States Steel Corp.	2,247	3.440	.3950
9. International Harvester Co.	2,113	3.232	.3820
10. Central Soya Co.	2,070	3.164	.3640
11. Darling & Co.	1,885	2.835	.3350
12. Inter Lake Iron Corp.	1,800	2.747	.3160
13. Republic Steel Co.	1,412	2.158	.2480
14. Crane Co.	1,376	2.103	.2420
15. Armour & Co.	999	1.525	.1750
16. W. B. Brown Bird & Son Co.	972	1.485	.1710
17. International Harvester Co.	968	1.480	.1700
18. The Glidden Co.	841	1.287	.1480
19. Wm. Wrigley Jr. Co.	826	1.262	.1450
20. Darling & Co.	792	1.210	.1390
21. Container Corp. of America	783	1.195	.1370
22. Bird & Son	670	1.022	.1180
23. E. J. Brach & Sons	506	0.772	.0888
24. Illinois Meat Co.	438	.670	.0771

INDUSTRIAL (contd).	SO_2 tons per year	SO_2 sub-percent	SO_2 grand percent
25. American Can Co.	426	.651	.0748
26. Tribune Co.	404	.618	.0711
27. General Electric	344	.526	.0605
28. Horween Leather Co.	308	.471	.0541
29. Joanna Westrn-Mills-Mans	301	.470	.0528
30. United States Steel Corp.	294	.450	.0517
31. Arvey Corp. Delaware Iron Co. Div.	243	.372	.0427
32. Hammond Warehouse Co.	232	.355	.0408
33. Great Lakes Carbon	221	.338	.0388
34. Wesson Oil & Snowdrift	203	.310	.0357
35. Rheem Mfg. Co.	189	.288	.0332
36. Rock-Ola Corp.	186	.285	.0327
37. Pettibone Mulliken Corp.	177	.271	.0311
38. National Biscuit Co.	166	.254	.0292
39. Western Felt Works	163	.248	.0286
40. Superior Tanning Co.	161	.245	.0283
41. Standard Brands	156	.238	.0273
42. Hygrade Food Products	155	.237	.0272
43. W. F. Hall Printing Co.	152	.232	.0267
44. General Rendering Co.	148	.226	.0260
45. Garden Baking Co.	144	.220	.0253
46. The Cuneo Press Inc.	141	.216	.0248
47. Handy Button Machine Co.	131	.201	.0230
48. American Oil Co.	129	.197	.0226

INDUSTRIAL (contd.)		SO_2 tons per year	SO_2 sub-percent	SO_2 grand-percent
49.	Chicago Rawhide Mfg. Co.	127	.194	.0222
50.	Stewart-Warner Corp.	124	.190	.0218
51.	Belden Mfg. Co.	106	.162	.0186
52.	Corn Products Co.	102	.156	.0179
53.	Bell Fibre Products	96	.147	.0169
54.	Pure Asphalt Co.	94	.144	.0165
55.	Bell Fibre Products	92	.141	.0161
56.	Ward Baking Co.	92	.141	.0161
57.	Borg-Warner Corp.	91	.139	.0160
58.	Armstrong Paint & Varnish	90	.138	.0158
59.	Inter Chemical Corp.	89	.136	.0156
60.	Squire Dingee	82	.125	.0144
61.	American Licorice Co.	81	.124	.0142
62.	Hewitt-Robins, Inc.	81	.124	.0142
63.	Revere Copper Brass	79	.121	.0139
64.	Allied Chemical	78	.119	.0137
65.	Goldblatt Bros. Inc.	78	.119	.0137
66.	Chicago Carton Co.	77	.118	.0135
67.	Miehle-Goss-Dexter Inc.	76	.116	.0134
68.	Libby, McNeill & Libby	75	.115	.0132
69.	Lanzit Corrugated Box Co.	74	.113	.0130
70.	Stone Container Co.	74	.113	.0130
71.	Continental Can Co.	73	.112	.0128
72.	R. R. Donnelly Co.	71	.109	.0125
73.	Illinois Packing Co.	67	.103	.0118

INDUSTRIAL (contd.)	SO_2 tons per year	SO_2 sub-percent	SO_2 grand percent
74. Kraft Foods	67	.103	.0118
75. Tee-Pak Inc.	67	.103	.0118
76. Boweys Inc.	66	.101	.0116
77. Ekco Products Co.	66	.101	.0116
78. Chicago Curled Hair Co.	63	.096	.0111
79. Rosens Bakery Inc.	63	.096	.0111
80. Griffith Labs Inc.	63	.096	.0111
81. Novo Ind.	62	095	.0109
82. Victor Mfg. & Gasket Co.	62	.095	.0109
83. National Lead Co.	61	.093	.0107
84. Illinois Moulding Co.	59	.090	.0104
85. Appelton Electric Co.	58	.089	.0102
86. Motorola Inc.	58	.089	.0102
87. Reliable Packing Co.	58	.089	.0102
88. Pyle-National Co.	58	.089	.0102
89. Peter Hand Brewery Co.	55	.084	.0097
90. Pullman Incorporated	55	.084	.0097
91. Huch Leather Co.	55	.084	.0097
92. Zenith Radio Corp.	55	.084	.0097
93. Ford Motor Co.	53	.081	.0093
94. Hawthorne Melody Inc.	53	.081	.0093
95. Chicago Molded Products	52	.080	.0091
96. National Lead Co.	52	.080	.0091
97. The Borden Co.	52	.080	.0091

INDUSTRIAL (contd.)		SO_2 tons per year	SO_2 sub-percent	SO_2 grand percent
98.	Phoenix Metal Cap Co.Inc.	51	.078	.0090
99.	Martin Senour Co.	51	.078	.0090
100.	Others	11,483	17.511	2.0100
	Sub Total	65,422	100.000	
	Grand Percent.			11.5000
	GRAND TOTAL	568,885		100.0000

*Data of 1964.

CHICAGO AIR POLLUTION DISPERSION MODEL

Appendix II

Department of Air Pollution Control

City of Chicago

THE FOLLOWING QUESTIONNAIRE IS INTENDED TO PROVIDE THE AIR POLLUTION ANALYST WITH HOURLY HIGH-SULPHUR FUEL CONSUMPTION DATA FOR THE YEARS 1966-67. IF YOUR FIRM CAN PROVIDE HOURLY FUEL USE DATA, PLEASE SUBMIT THIS DATA AND DISREGARD THIS QUESTIONNAIRE. IF THIS TYPE OF DATA IS AVAILABLE, BUT IS INCONVENIENT TO RECORD, CLERICAL ASSISTANCE WILL BE MADE AVAILABLE UPON REQUEST FROM R. J. VOTRUBA - CHICAGO DEPARTMENT OF AIR POLLUTION CONTROL-PHONE 744-4078.

1 Does your firm retain Steam Charts? _____Yes _____No. If so can they be obtained for Recording & Analysis ___Yes _____No

What is the Operating Pressure of your steam system _____psig.

What is the efficiency of the boilers? _____% EFF.

What is the BTU Rating of the Fuel ______BTU

11 TOTAL AMOUNT OF FUEL CONSUMED IN 1966-67

Tons of Coal_____Average.% Sulphur in Coal________________

Gals of Fuel Oil_______Average. %Sulphur in Fuel Oil __________

_______Hourly _______Daily________Weekly______Montly______Yearly

IF THE ABOVE INFORMATION CAN BE FURNISHED, DISREGARD 11A. IF NOT, PLEASE SUPPLY THE FOLLOWING INFORMATION WHICH WILL HELP TO PROVIDE THE NECESSARY DATA.

11A NAME & PHONE NUMBER OF FIRMS FROM WHICH FUEL WAS PURCHASED

____

____

WOULD YOUR FIRM BE WILLING TO HAVE FUEL DATA FURNISHED BY THE UTILITY COMPANIES _____YES _______NO

111 AVERAGE PROCESS FUEL CONSUMPTION FOR MANUFACTURING (NOT TO INCLUDE FUEL CONSUMPTION FOR SPACE HEATING)

CHECK DAYS PER YEAR HEATING PLANT IS NORMALLY IN OPERATION_________

CHECK ONE OF THE FOLLOWING

_____________TONS OF COAL PER	_________HOUR
	_________DAY(24 HRS)
_____________GALS OF OIL PER	_________WEEK
	_________MONTH

FOR PLANTS OPERATING ON A ONE SHIFT PER DAY BASIS, WHAT IS THE AVERAGE FUEL CONSUMPTION BETWEEN THE END OF ONE WORKING DAY AND THE START OF THE NEXT WORKING DAY__________TONS OF COAL __________GALS. OF OIL.

FOR PLANTS OPERATING FOR MORE THAN ONE SHIFT, WHAT IS THE AVERAGE FUEL CONSUMPTION DURING THE 1ST SHIFT __________TONS COAL _____GALS OIL.
DURING THE 2ND SHIFT __________TONS COAL________ ________ GALS OIL.
DURING THE 3RD SHIFT ________TONS COAL ________GALS OIL.

1V AVERAGE SPACE HEATING FUEL CONSUMPTION FOR COMBINED PROCESS AND SPACE HEATING PLANTS.

DAYS PER YEAR HEATING PLANT IS NORMALLY IN OPERATION __________

__________TONS OF COAL PER ________HOUR

________DAY(24 HRS)

__________GALS OF OIL PER ________WEEK

________MONTH

V (ANSWER ALL OF THE FOLLOWING)

DAYS PER WEEK HEATING PLANT IS NORMALLY IN OPERATION _______DAYS
NUMBER OF SHIFTS HEATING PLANT IS NORMALLY IN OPERATION FOR COMBINED PROCESS AND SPACE HEATING __________DAYS

DOES THE PLANT OPERATE ON A ONE SHIFT PER DAY BASIS?____YES_____NO
IF SO WHAT TIME DOES THE HEATING PLANT START OPERATION ________ AM PM
IS THE HEATING PLANT SHUT DOWN AFTER THE WORKING DAY HAS ENDED?

__________Yes __________NO

WHAT TIME __________AM PM

IS THE HEATING PLANT PARTIALLY SHUT DOWN AFTER THE WORKING DAY HAS ENDED? DAY _______YES _______NO WHAT TIME __________AM PM
DOES THE HEATING PLANT OPERATE DURING MORE THAN ONE SHIFT?_______
2ND SHIFT________3RD SHIFT. IF SO WHAT TIME DOES THE HEATING PLANT START OPERATION DURING THE 2ND SHIFT?_________AM PM THE 3RD SHIFT _______AM PM. DOES THE HEATING PLANT SHUT DOWN AFTER THE 2ND SHIFT?
______YES _______NO. IF SO AT WHAT TIME __________AM PM

DOES THE HEATING PLANT SHUT DOWN AFTER THE 3RD SHIFT? ____YES____NO
IF SO AT WHAT TIME ________AM PM. DOES THE HEATING PLANT PARTIALLY SHUT DOWN AFTER THE 3RD SHIFT? _____YES____NO. IF SO AT WHAT TIME ____AM PM

DURING PERIODS OF HEATING PLANT OPERATION WHAT AVERAGE TEMPERATURE IS MAINTAINED WITHIN THE PLANT __________°F?

V1 IS THE SAME TYPE OF FUEL USED FOR BOTH PROCESS AND SPACE HEATING?

______YES _______NO.

IF NOT PLEASE INDICATE WHAT TYPES OF FUEL ARE USED FOR PROCESS AND

SPACE HEATING _____GAS_____OIL______COAL

FOR WHAT MONTHS IS THIS TRUE? (CIRCLE THE MONTHS)

J F M A M J J A S O N D

SPACE HEATING _____GAS_____OIL_____COAL

FOR WHAT MONTHS IS THIS TRUE (CIRCLE THE MONTHS)

J F M A M J J A S O N D

V11 DOES THE HEATING PLANT OPERATE ON WEEKENDS? ____YES_____NO.

INSERT "P" FOR THE WEEKEND DAY THE HEATING PLANT OPERATED FOR PROCESS AND "S" FOR THE WEEKEND DAY THAT THE HEATING PLANT OPERATED FOR SPACE HEATING. FOR THE WEEKEND DAY THAT THE HEATING PLANT OPERATED FOR BOTH PROCESS AND SPACE HEATING, INDICATE WITH "(SP)" IN THE TABLE BELOW

SHIFT		JAN	FEB	MAR	APRIL	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC
1st	SAT. SUN.												
2nd	SAT. SUN.												
3rd	SAT. SUN.												

V111 HOW MANY STACKS HAS YOUR PLANT _______

WHAT IS THE HEIGHT OF EACH STACK IN FEET FROM GRADE?

1. ____FT 2. _____FT 3. _____FT 4. _____FT

WHAT IS THE DIAMETER OF THE STACK?

1. ____FT 2. _____FT 3. _____FT 4. _____FT

WHAT IS THE STACK TEMPERATURE FROM EACH?

1. ____FT 2. _____FT 3. _____FT 4. _____FT

AT WHAT ELEVATION FROM GRADE IS THIS TEMPERATURE MEASURED?

1. ____FT 2. _____FT 3. _____FT 4. _____FT

WHAT ARE THE STACK EXIT VELOCITIES?

1. ____FT 2. _____FT 3. _____FT 4. _____FT

THERE ARE ____STACKS FOR PROCESS HEATING AND/OR INCINERATION

THERE ARE ____STACKS FOR SPACE AND/OR HOT WATER HEATING

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